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CHARACTERIZATION AND UTILIZATION OF MUNICIPAL AND UTILITY SLUDGES AND ASHES

VOLUME II. MUNICIPAL SLUDGES

Dayton University

National Environmental Research Center

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CHARACTERIZATION AND UTILIZATION OF MUNICIPAL AND UTILITY SLUDGES AND ASHES

Volume II. Municipal Sludges

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Volume II

Municipal Sludges

by

N. L. Hecht, D. S. Duvall, and A. S. Rashidi
University of Dayton Research Institute
Dayton, Ohio 45469

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Project Officers

R. A. Carnes and D. F. Bender
Solid and Hazardous Waste Research Laboratory
National Environmental Research Center
Cincinnati, Ohio 45268

NATIONAL ENVIRONMENTAL RESEARCH CENTER
OFFICE OF RESERACH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

Wastewater and water treatment sludges pose a serious disposal problem in the United States. The quantities of these sludges, their composition, and handling and treatment techniques now employed have been compiled in this report. Environmental contamination in disposing of these sludges is of major concern. On the other hand, utilization of the sludges as a valuable resource continues to be an important research objective.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

ABSTRACT

A comprehensive characterization and evaluation was performed of disposal and utilization practices for sludges from municipal wastewater and water treatment plants. The nature and quantities of the sludges were discussed. Various sludge handling and treatment techniques were detailed. Problems encountered in sludge disposal were reviewed, and the economics of wastewater sludge disposal were discussed.

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SUMMARY

The primary objective of a wastewater treatment plant is to prevent pollution of streams, lakes, and ground water supplies, by removing the solid pollutants from the wastewater. The solids removed are in the form of a liquid slurry, called sludge. Sludges are concentrated pollutants. They must be disposed of in a manner that assures public health and environmental safety. Furthermore, disposal methods applied must account for recycling of the organic and useful material of the sludge back to nature; also, the disposal method should be economically feasible.

Sludge handling, treatment and disposal requires many steps, including: concentration, stabilization, conditioning, dewatering and drying, transporting, and solids reduction. A flow diagram of the most common methods used for sludge processing and disposal is shown in Figure 1.

Concentration processes are applied primarily to increase the solids content of the sludge, thus reducing its volume significantly. Sludge concentration might be desirable when: (1) liquid sludge is applied to farmland; (2) sludge is disposed of in the sea (barging); and (3) when savings of chemicals, heat energy, and auxillary fuel in the subsequent steps are questions of concern. Methods used for sludge concentration or thickening include: (1) gravity thickening; (2) dissolved air-flotation; and (3) centrifugation. Gravity thickening is the most widely used, simplest and least expensive sludge concentration method. This process is basically the same as sedimentation settling, but relitively slow in action. The degree of sludge concentration obtained and the efficiency of thickener operation depends on such factors as: (1) initial solids concentration and temperature of the sludge in the thickener; (2) type of sludge and volitile content; and (3) addition of chemicals and inert weighing agents. Typical concentration that can be obtained for various types of sludges are: 8% for primary, or trickling filter sludges, 5% for modified aeration; and 3% for activated sludge. Flotation thickening of sludge is becoming increasingly popular. The basic principle in flotation thickening is to attach minute air bubbles to the suspended solids of the sludge. This reduces the specific gravity of the solid particles below that of water and causes the solids to separate from the liquid phase while moving in an upward direction.

Four methods of flotation thickening that are used in wastewater treatment plants include: (1) dispersed air flotation; (2) dissolved air pressure flotation; (3) dissolved air vacuum flotation; and (4) biological flotation. Among the above four methods, dissolved-air flotation, and biological flotation have received wide use because of the higher solids concentration obtained. The major variables influencing flotation thickening include: (1) pressure; (2) recycle ratio; (3) feed solids concentration; (4) detention period; (5) air to solid ratio; (6) type and quality of sludge; (7) solids and hydraulic loading rates; and (8) use of chemical aids. Flotation thickeners are used primarily in conjunction with waste activated sludge. Typical concentration obtained from combined primary and activated sludge is 6%. For activated sludge alone, the concentration is 4%; and when chemical aids are employed, 6%. Centrifugation of sludge for thickening and dewatering purposes has long been practiced in wastewater treatment plants. Typical concentration obtained is 7%. Higher concentration is possible using chemical aids.

Raw sludge contains a substantial amount of organic material. Sludges provide food for microorganisms which grow in and upon them. These microorganisms are mostly of fecal origin and many of them are pathogenic, which may be definite health hazards. Therefore, decomposition of the organic material, or sludge stabilization seems an obvious necessity. Methods applied for stabilization of wastewater sludges include: (1) anaerobic digestion; (2) aerobic digestion; (3) composting; (4) lagooning; (5) heat treatment; and (6) chemical stabilization.

Anaerobic digestion of sludge involves decomposition of organic material in the absence of free oxygen. Digestion occurs in two separate stages, called liquefaction and gasification stages. The end product of the first stage is utilized in the second stage as fast as it is produced. Responsibilities of the group of microorganisims (acid forming bacteria) in the first stage are the hydrolysis and fermentation of the complex organic compounds to simpler organic acids. A responsibility of the group of microorganisims (methane forming bacteria) in the second stage is to convert the organic acids to methane gas and CO_2. Anaerobic sludge digestion is the oldest method of stabilization, and it will continue to be used particularly at small sewage treatment plants and in large coastal cities. Factors effecting digestion of wastewater in sludges include: sludge type and volatile content; digester temperature; digestion detention period; feed sludge concentration;

degree of digester mixing; digester loading rates; and presence of toxic materials. Three types of anaerobic digesters being used in wastewater treatment plants are: (1) conventional digester, (2) high-rate digesters, and (3) anaerobic contact process.

Aerobic digestion is a biological process during which gross oxidation is completed in two stages: (1) direct oxidation of any biodegradable matter by biologically active masses of organisms, and (2) oxidation of microbial cellular material by endogenous respiration. Aerobic digestion has been used extensively in treating waste activated sludge. Factors effecting design and operation of this process include: rate of sludge oxidation; sludge temperature; oxygen requirements of the system; sludge loading rates; sludge age; sludge solids characteristics; and characteristics of the residue and supernatant liquid. In aerobic digestion volatile solids reduction of up to 50% can be obtained. Rate of reduction is very high in the initial 10-15 days, whereas after 15 days the rate of reduction slows down drastically.

Composting of sludge can be defined as the decomposition of organic waste by aerobic, thermophilic organisms to produce a stable humus-like material. The compost produced can be used as a soil conditioner or fertilizer depending on its nutrient content. Composting methods used include: (1) indoor (mechanical), and (2) outdoor (windrows and bins) processes. In the mechanical composting process there are three phases. These are: (1) dewatering of the sludge, (2) composting, and (3) final curing. The factors which affect the composting process include: mixing moisture content; percent of recycled compost; aeration; and temperature and pH. Volume reduction of about 70% with solids reduction of 30% can be obtained. The heat generated (140 ± °F) is sufficient to destroy most of the pathogenic bacteria. Composting of wastewater sludge, mixed with refuse, has been found to be more advantageous than composting of either sludge or refuse alone.

Sludge lagoons have been used for sludge stabilization purposes quite frequently, particularly in small plants. They are relatively inexpensive and very simple to operate. Where a lagoon is used for digestion of raw sludge, odor, and insect breeding may be problems. Design parameters commonly used are: land area, climate, subsoil permeability, lagoon depth, sludge loading rate, sludge characteristics and types.

Heat treatment of the wastewater sludge has increasingly gained popularity in recent years. When sludge is heated at high temperatures under pressure, the gel-like structure of the sludge is destroyed and the bound water is liberated. The resulting product is sterilized, deodorized and readily dewaterable. Major processes used include: (1) Zimpro process, (2) Porteous process, and (3) Farrer system.

Application of the heat treatment processes, particularly the Zimpro process (also called wet oxidation), in the treatment of wastewater sludge, is growing rapidly. Operation of these processes includes the following steps: (1) sludge is ground up and pressurized to the selecting operating pressure; (2) sludge is pre-heated by passing it through a heat exchanger; (3) the pre-heated sludge (in the case of wet oxidation, mixture of the sludge and air) is fed into the reactor, where sludge is further heated to about 300 to 400 °F for a period of 30 to 60 minutes; (4) the heat conditioned sludge is cooled by heat exchange with the incoming sludge; (5) gases are separated and released through a catalytic after burner or similar devices; and (6) stabilized sludge is concentrated and dewatered to about 40 to 50% solids content without use of chemicals. It has been observed that heat treatment destroys most of the pathogens. The major difference between the Zimpro process and the other two is that the Zimpro process air is introduced into the reactor, and it is not in the Porteous or Farrer systems.

Chemicals have also been used to stabilize the sludge produced from wastewater treatment processes. The two types of chemicals that are very common are chlorine and lime. Both chemicals have been found to be very effective in microbial destruction.

Other methods used for sludge stabilization include solvent extraction, and electrical treatment. Though these methods are very effective and technically promising, they are not economically feasible and many operational problems are associated with them.

Sludge is conditioned principally to improve its dewatering characteristics. Various methods of sludge conditioning that are currently being practiced include: (1) elutriation, (2) chemical conditioning, (3) freezing, and (4) addition of flocculating agents and filter aids, such as fly ash, diatomaceous earth, etc. The sludge moisture content can be reduced to about 70% by means of proper conditioning, followed by a dewatering process.

Elutriation is a washing operation which removes sludge constituents that interfere with sludge thickening and dewatering processes. As the elutriation comes in contact with the sludge particles, dispersants such as carbonates and phosphates are extracted from the sludge as well as non-settleable fine particles, the products of decomposition, and the toxic materials. The elutriation operation can be performed as a batch or continuous process. It could be single stage with single contact between the solids and the liquid, or it could be multistage contact in one or more stages or multistage counter current contact.

Use of chemicals to condition sludge results in coagulation of the solids and the release of the absorbed water from the solid particles. The most common types of chemicals used in conditioning of wastewater sludge include: ferric chloride (either alone or combined with lime); a combination of ferric chloride and alum; or lime alone. Ferric chloride is used in plants dewatering activated sludge, where ferric chloride and lime are used in plants dewatering raw and/or digested sludge. The chemical dosage required for a given sludge is determined in the laboratory. Polyelectrolytes have gained much popularity in recent years as a sludge conditioner. Dewaterability of the sludge and solids content of the filter cake solids captured during the elutriation have significantly been improved in sludge which was conditioned with polymers. Dosage rates of polymers as compared with other chemicals are significantly lower, on the order of 1/50 to 1/100 times of other chemicals.

Freezing has also been applied to sludge conditioning. The conditioning effect produced by freezing is believed to result from dehydration, and the pressure exerted on the sludge particles by the ice structure. A significant increase in solids content and dewaterability of the sludge is attained by slow freezing and thawing, provided that the freezing cycle is complete. Freezing is generally used in cold climates, however, it can be applied in mild climates if the sludge is applied in thin layers 0.5 to 1.0 inch thick.

Fly ash and other filter aids such as diatomaceous earth, sawdust, newsprints,etc., have also been used for sludge conditioning. These materials together with the solid phases of the sludge form a porous, permeable and rigid lattice structure which filters particulates but allows passage of liquid. The amount of fly ash required to improve filterability of activated sludge ranges from 500 to 700% of the initial solids content of the sludge; whereas, for digested sludge it ranges from 100 to 150%.

Sludge dewatering is generally applied to serve such purposes as: reducing the volume of the sludge; reducing the moisture content of the sludge, thus, reducing the fuel costs when sludge is dried or incinerated; and increasing the solids content so that the sludge is easily handled and disposed of. The methods commonly used for sludge dewatering include: (1) sand bed drying; (2) centrifugation; (3) vacuum filtration; (4) filter press; (5) heat drying; and (6) vibration.

Drying of the sludge on open or covered sand beds is the most common dewatering method presently in use. Open sand bed dewatering is probably the least expensive method of all. It has been used extensively in small (<10,000 pop.) communities. Variables effecting dewatering rates include: (1) climate and atmospheric variations; (2) sludge depth applications; (3) sludge moisture content; (4) origin and type of the sludge; (5) sludge age; (6) drying beds construction; and (7) presence or absence of coagulants. In general, drainage is the predominant dewatering mechanism during the first 2 to 3 days after the application of the sludge, during which, 60 to 85% of the sludge moisture loss occurs. After 2 to 3 days, evaporation becomes the major factor and its rate depends solely on the climatic conditions. The optimum sludge application depth is about 9 inches.

Centrifuges have also been used for municipal sludge dewatering purposes. The three major types of centrifuge used are: (1) basket-design centrifuges; (2) disk-design centrifuge; and (3) solid bowl conveyor centrifuge. The solid bowl conveyor centrifuge has been the most effective of all. Parameters that effect the efficiency of the unit include machine variables, such as bowl design, bowl speed, pool volume, and conveyor speed, and pitch; and process variables, such as feed rate, solid characteristics, feed consistency, temperature, and chemical aids. Total solids of the cake ranges from 18 to 35%, and the solids recovery varies from 50 to 90% without use of chemicals, and 90 to 98% when chemicals are used.

Vacuum filters are the most common type of mechanical dewatering facilities used today, particularly when incineration is used for final disposal. Various types of vacuum filters used include: (1) drum-type filters; (2) string-discharge filters; (3) belt-type filters; and (4) coil-type filters. Factors effecting dewaterability of the sludge include: (1) sludge solids content; (2) sludge age and temperature; (3) sludge and filtrate viscosity; (4) sludge compressibility; and (5) the nature of the sludge solids. Chemicals are frequently used for conditioning the sludge. Cake solids content for various types of sludges, ranges from 15 to 35%.

Filter presses and plug presses have also been used for sludge dewatering purposes. However, their use is very limited in the U.S. because of the high cost of manual labor and maintenance of the system.

Wastewater sludge has been heat dried particularly in conjunction with production of fertilizer or soil conditioner, in which sludge is generally dewatered to a 10% moisture content, utilizing heat dry facilities. Heat drying permits the end products to grind well, reduces sludge weight and odor, destroys pathogens and most important of all provides an ultimate means of disposal by recycling the organic material back into the land. The various types of equipment used for sludge drying include: (1) flash drying system; (2) multiple hearth dryer; (3) rotary kiln dryer; and (4) atomized spray dryer. The most common types are the flash drying and multiple hearth systems. Because of the high costs involved in sludge drying, sludge is generally dewatered by mechanical means prior to drying. The sludge drying temperature commonly used is about 700°F.

Common methods for conveying the resulting liquid or dried sludge from the wastewater treatment plant to a final disposal site include: (1) barging transport; (2) pipeline transport; (3) truck transport; and (4) railroad transport. Barging is generally utilized in coastal cities. Approximately 4.5 million tons (on a wet basis) of wastewater sludge was barged to the sea in 1968. Liquid treated sludge is generally thickened to about 4 to 10% solids content prior to barging. Pipeline transporting of sludge is very common. Its uses include: transport to farmland, to land for land reclamation purposes, to disposal site at sea, and others. Truck transporting of liquid and dried sludge from the plant to the final disposal site is a very common method particularly in smaller treatment plants.

Sludge is generally incinerated for two main reasons: (1) volume reduction, and (2) solids reduction and sterilization. Methods used for sludge incineration are the same as those mentioned for sludge drying purposes with some process modifications. Incineration temperature ranges from 1350 to 1600°F. Sludge is generally dewatered to about 70% moisture content prior to incineration. Sludge combustion is effected by a number of factors, including sludge calorific value, sludge volatile content, and sludge inert content. A typical calorific content of the sludge is about 10,000 Btu/lb of volatile solids. A complete incineration process involves two steps: (1) drying, and (2) combustion. The first step requires auxilliary fuel, whereas the second step could be an endogenous process, depending on the volatile content of the sludge and deodorizing requirements. Sludge incineration has become very common, particularly in large cities, despite the high costs involved. The major types used are multiple hearth and flash drying units. The principal end products of incineration are gases (CO_2, SO_2, NO_x), and inert ashes and residues. It appears that incineration of the sludge involves some degree of hazardous environmental and health effects; however, sufficient data are not available to establish these potential hazardous effects.

Pyrolysis of wastewater sludge has also been practiced to produce a marketable by-product (absorbent materials). The pyrolysis unit generally consists of a closed stainless steel cylinder, in which the sludge is retained for 60 to 90 minutes in the absence of air at a temperature of 1200°F.

The main objectives for the application of physical, biological and chemical processes in a wastewater treatment plant are to remove and concentrate that portion of the wastewater that is responsible for its offensive nature. The sludge which constitutes a significant portion of the total pollutants removed is by far the most important by-product of the wastewater treatment processes. Handling and disposal of such concentrated pollutants present some of the most complex problems that engineers and plant operators face. In addition, the cost of the sludge treatment and disposal is very high-as much as 50% of the total capital and operating costs of the entire waste treatment processes.

Sludge consists of a mixture of organic, and inorganic solid phases, suspended in an aqueous solution. Sludges are the solids which settle from the water and wastewater, and the colloidal particles that are precipitated by biological flocculation and chemical coagulation. The sludge has a very high moisture content ranging from 90 to 99%.

The characteristics of the sludge are dictated by such factors as: source of the wastewater, i.e., municipal, or municipal combined with industrial; the degree of treatment the wastewater receives, i.e., primary, secondary, advanced,or any combination of the above; the type of treatment processes to which the sludge is subjected, i.e., raw (untreated), digested, digested and elutriated; and the type of collection system, i.e., separate or combined systems. In a municipal water treatment plant, sludge is obtained from two major sources: sedimentation basins, and filter backwashes. The characteristics of this sludge depend upon the source of the raw water and the type of the processes utilized.

The quantity of sludge generated by municipal wastewater treatment plants throughout the U.S. is about 13 million tons/year on a dry solids basis. Intensified water quality enhancement programs, stringent water pollution standards, and the construction of additional wastewater treatment facilities, and/or the upgrading and expansion of the existing facilities, and the continual growth of population will contribute significantly to the increase of the sludge quantities being produced. The quantities of sludge produced by water treatment plants are far less than those produced by wastewater treatment plants, amounting to 4 million tons/year on a dry solids basis in the U.S.

In general, primary sludge is gray in color, slimy in nature, and gives off an offensive odor. It has solids content ranging from 1 to 5 %. Activated sludge is generally brown in color. When the color darkens, it indicates septic conditions. The fresh sludge has no characteristic odor, but in septic conditions it has the disagreeable odor of putrefaction, and the solids content ranges from 3 to 8%. Trickling filter humus has a brownish color; the fresh sludge has relatively inoffensive odor, but when it undergoes decomposition, it gives off a very offensive odor. The solids content of the humus ranges from 3 to 7%. Digested sludge has a dark brown to black color and contains large quantities of gases. A completely digested sludge has an odor similar to that of hot tar or burnt rubber. It has solids contant ranging from 0.2 to 4.0%.

The solids fraction of the wastewater sludge is primarily composed of biodegradeable material (30%), stable organic matter (35%), and inert material (35%) . Further, about 60% of the total solids are dissolved solids, 20% are settleable solids, and 20% are colloidal solids.

The characteristics effecting ultimate disposal and effective utilization of the wastewater sludges include: settling characteristics, specific resistance, flow characterisitcs, calorific values, chemical composition, and fertilizing ingredients of the sludge.

Settling characteristics of the sludge are vital parameters, since one of the primary objectives in sludge treatment is to concentrate the residues and reduce the overall volume of the sludge. In the design of treatment processes, zone settling and compression settling are of major importance; however, discrete settling and flocculant settling may also occur at a given period during sedimentation. The Talmadge and Fitch method is generally applied to determine the settling tank area requirements for both sludge thickening and clarification purposes, for zone settling. The concentration of the settled sludge is effected by such factors as:

wastewater characteristics; type of biological treatment the wastewater receives; design and operation of the settling tank; promotion of settling, using mechanical means or chemicals; settleable solids characteristics; solids concentration in the original suspension; and sludge detention time, etc. The solids concentration of the sludge varies from 0.5 to 10% for raw sludges and from 2 to 10% after digestion.

Another physical characteristic of the sludge that is important in the design of treatment processes such as vacuum filters, centrifuges, and drying beds is the specific resistance. A specific resistance concept is generally used to evaluate the filtration characteristics of the sludge; by this is meant the difficulty encountered in removing water or conversely, the ability of the sludge to retain water. Specific resistance values for wastewater sludge range from 10×10^7 sec^2/gr, when chemical coagulants are employed, to as high as 2800×10^7 sec^2/gr for pure activated sludge. Low values are indicative of a sludge with rapid draining or filtering characteristics, and for high values the reverse is true.

The heterogeneous nature of the wastewater sludge causes complex flow phenomena; consequently, the direct application of the existing hydraulic equations for measuring pipe friction loss is not adequate in most cases. Flow characteristics of the sludge become a significant parameter when liquid sludge is transported via pipelines to the disposal site. The most significant factor effecting sludge flow is the moisture content of the sludge. Based on the moisture content, the flow is classified as: (1) flow in suspension, and (2) plastic flow. Numerous methods for calculating critical velocities, head loss, and other flow characteristics are available in the literature.

Calorific value of the sludge is a vital parameter in the design and operation of sludge incinerators. Calorific value of the sludge combined with its ultimate analysis determines the quality of the sludge for incineration. The combustible fraction of the sludge ranges from 50% for digested sludge to 75% for raw sludge. The heat content of the sludge ranges from 5000 Btu/lb to 14,000 Btu/lb of combustible solids, for digested and undigested sludges respectively.

A proper assessment of the usefulness of the sludge can be made if its chemical composition is known. Analysis of the specific organic constituents of a sludge is important in predicting what conditions will prevail during dewatering and also helps in determining what specific effects the sludge might have on solids characteristics. The organic fraction ranges from 60 to 80% on a dry weight basis, for primary sludge; 62 to 75%, for activated sludge; and 45 to 60%, for digested sludge. The organic content of the sludge is usually measured from the BOD and volatile solids determination. However, more useful and implicit tools are the COD and TOC tests. Sludge also contains a variety of metallic ions, including toxic metals. Their relative concentrations depend mainly upon the origin of the wastewater.

Wastewater sludge contains many fertilizing elements. In comparison with commercial fertilizers, they are rated principally on their content of three substances: nitrogen, ranging from 0.8 to 10% as N; phosphorous, ranging from 1 to 4% as phosphoric acid; and potassium, ranging from 0.1 to 0.5% as potash.

Characteristics of the sludges from water treatment plants are highly variable depending on such factors as: sources of raw water; type of treatment processes employed; type of chemicals added; efficiency of unit operation; degree of solids removed; and the time between basin and filter backwash clean-out. The significant parameters for characterizing these sludges include: solids; settleability; filterability; viscosity; and to a lesser extent, coliform content, BOD, COD and chemical composition.

The two major types of sludge resulting from a municipal water treatment plant are: (1) basin sludges, and (2) filter backwash wastes. Basin sludge is comprised of the organic, inorganic, and biological organisms present in the raw water and may be in a state of solution, colloidal suspension or readily settleable form; or, it may be mixed with coagulant aids employed in the treatment process. Basin sludge appears as a fluffy agglomeration of chemically precipitated and organic debris, with a high moisture content (96 - 99%). The color of the sludge approaches yellow-orange, pale-green, dark-brown and sometimes black, depending upon the type of chemicals used, nature of the impurities extracted, and stage of decomposition of the organic material. Filter backwash waste essentially contains a finer fraction of the basin sludge in a much lower concentration, plus a small portion of the filter media itself.

The ultimate disposal of the vast quantities of sludge being generated throughout the U.S. is one of the most complex problems facing sanitary engineers today. It appears that the disposal problem will continue to grow due to tightening of water, air and land pollution control standards, lack of land availability resulting from rapid growth of urbanized communities, growth of population, etc.

Numerous methods for disposal or utilization of municipal sludges have been practiced. These methods are summarized in Table 1. Ultimate disposal of the sludge is the last step in the treatment processes. It must comply with the state, interstate and federal standards and requirements; it should not adversely effect the surface or ground water, air, or land surfaces; it should be economically feasible; and it should assure public health safety.

Ocean disposal of wastewater sludge by barging or through submarine outfalls is very common practice for major coastal cities. It is the most economical disposal method for coastal cities when compared with the alternative methods. However, because of the observed adverse environmental effects of this method, indications are that this method may be banned in the future.

Land spreading of treated liquid sludge on crop lands appears to have gained much popularity in the last decade. It offers many advantages, including: (1) economy; (2) recycling of water, nutrients, and organic materials; (3) a final treatment process and ultimate disposal; and (4) freedom from nuisance if done properly. Possibilities of toxic metal accumulation and surface and ground water contamination appear to be negligible; however, extensive research is required to confirm this.

Wastewater sludge has been utilized to reclaim sandy soils and strip mine spoils by converting them into valuable crop land or recreation parks. Numerous projects throughout the U.S. are underway. It appears that this is a satisfactory method of sludge disposal to the extent that it does not cause pollution; it is relatively economical; and it utilizes the organic content of the sludge for beneficial purposes.

Application of dried treated sludge on land as fertilizer, or soil conditioner is a viable ultimate disposal method. From the standpoint of fertilizing ingredients content, dried sludge may not compete with commercial fertilizer, however several municipalities have reported satisfactory marketing of the dried sludge. A growing demand for the use of dried sludge on parks, golf courses, and lawns is apparent.

Recovery of certain by-products such as Vitamin B-12, grease, metals (Ag, Cu, Ti, etc.), absorbent material, etc. from wastewater sludges has been reported in the literature. However, marketing and the value of the product and associated marketing problems have not been worked out. In general, the market place determines the by-product specifications; and, in most cases, the specifications

TABLE I

PRESENT METHODS OF MUNICIPAL SLUDGE DISPOSAL AND/OR UTILIZATION

Wastewater Treatment

1. Ocean dumping or discharging
2. Land spreading of liquid sludge.
3. Land reclamation.
4. Lagooning and landfilling.
5. Disposal of dried sludge as fertilizer or soil conditioner.
6. Underground disposal.
7. Incineration and landfill of ash.
8. By-product recovery.

Water Treatment

1. Direct discharge to streams, ocean or lakes.
2. Lagooning of the sludge.
3. Agriculture utilization.
4. Discharge to sewers.
5. Disposal in sanitary landfill.
6. Application of sludge to strip mines.
7. By-product recovery.

are rigid concerning product purity and concentration. A great amount of development and additional research needs to be done before by-product recovery appears to be practical.

Disposal of the sludge generated from municipal water treatment plants has been predominantly dumped into the nearest available water course. It appears that an intensified effort is in progress by the water industry and other organizations, to put the task of handling and disposal of these wastes in the proper perspective. A majority of the states has banned direct discharge of these wastes into state or federally owned waters. Methods for disposal and utilization of these wastes presently in use are listed in Table 1.

Direct disposal of these wastes into a water course may not cause serious health hazards as compared with wastewater and wastewater sludges, because of low organic content. However, the high solids content of these sludges may color the receiving water, increase its turbidity, and may settle and form sludge beds, interferring with the natural aquatic life cycle. Disposal of these sludges into sanitary sewers has resulted in enhancement of the wastewater treatment process operation. However, it has some disadvantages, including precipitation and solids formation on the walls of the sewers if flow velocities are below 25 ft/sec; and in excessive amounts it may hinder the biological activities of the secondary process. Disposal of these wastes into sanitary landfills appears to have many advantages. However, leaching has been reported, when liquid sludge was applied in excessive amounts. Application of water softening plant sludge as an agricultural lime, or for reclaiming strip mine spoils has shown very promising results. When used as agricultural lime, care must be taken so that possible accumulation of toxic metals is prevented.

By-product recovery of the wastes from water treatment plants includes lime recovery, magnesium recovery, and alum recovery. Recalcination (lime recovery) from large softening plants has been very successful and has almost eliminated the disposal problem. Recovery of magnesium carbonate and utilization of it as a replacement for alum coagulant seems very promising. Recovery of aluminum sulfate from water purification wastes has been practiced very extensively in Japan and France. Although this process substantially reduces the volume of sludge for final disposal, complete separation of the impurities, such as iron, manganese, etc. is a difficult job.

INTRODUCTION

The fraction of wastewater which is primarily responsible for the offensive nature of the wastewater is removed by physical, biological, and/or chemical processes in a municipal water or wastewater treatment plant. These unwanted materials, which include grit, screenings, skimmings, and sludge, present a potential pollution hazard. These sludges which constitute a significant portion of the total wastes removed are by far the most important by-products of the waste treatment processes. Sludge handling and disposal represent some of the most complex problems for the engineers and operators.

Sludge consists of a mixture of organic and inorganic phases, suspended in an aqueous solution. Sludges are predominantly the solids which settle from the water and wastewater, and /or the colloidal particles that are precipitated by biological flocculation and chemical coagulation*. The sludge has a very high moisture content, ranging from 90 to 99%. Variations of moisture content and other characteristics, will depend on such factors as: wastewater origin, type of treatment processes to which both the wastewater and sludge had been subjected, and the type of sewerage system.

Proper handling and disposal of sludge is a serious problem today. Disposal practices must be consistent with an awareness of the aesthetics, pollution potentials, and economics. The magnitude of the sludge disposal problem is ever-increasing due to implementation of more stringent pollution control standards for water, land, and air along with the rapid growth of population (projected to reach over 350 million people by the year 2000, with over 85% living in the urbanized communities). Because technological advancement in the treatment and disposal of sludge has not kept pace with the advancements of water and wastewater treatment, the cost of sludge disposal may increase to the point where it will be as much as 50% of the total treatment costs (1). Bloodgood (2) states the problem of sludge disposal is as great, or greater than that of purifying the sewage. Thomson and Morgan (3) say that "the enigma of sewage treatment is the disposal of ever-increasing sludge". Dean (4) says disposal of the sludge has always been a problem and one that requires the expenditure of money without the production of anything that could be sold for a profit.

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* Sludges also include a fraction of the dissolved solid phases.

Various sludge disposal methods existing today include landfill, ocean disposal, deepwell injection, incineration, land spreading and land reclamation. Another possible method of disposal is outerspace dumping. However, not all of the above methods have solved the problem of ultimate disposal. The most promising ultimate disposal methods are: reuse and utilization of the sludge as soil fertilizer or soil conditioner; recovery and recycling of certain by-products; and land reclamation.

The purpose of this report is to summarize the information pertaining to wastewater and water treatment sludges that has been gathered through literature searches and personal contacts with individual investigators, research institutes, governmental agencies and other available sources.

SLUDGE ORIGIN AND TYPE

The characteristics of the sludge generated from water and wastewater treatment facilities are directly related to the source of the water and wastewater; the type of treatment processes to which the water, wastewater, and the sludge are subjected; the type of sewerage system; and the degree of treatment required. Considering these factors, sludges may be classified as follows:

- I. Sludge Origin
  - A. Municipal
    - 1. Domestic and industrial wastewater
    - 2. Potable water treatment plant
  - B. Industrial Wastewater Treatment
- II. Sludge Treatment Processes
  - A. Raw (untreated)
  - B. Digested
    - 1. Aerobic
    - 2. Anaerobic
  - C. Digested and Elutriated
  - D. Air Floating Sludge
  - E. Chemically Treated
  - F. Heat Treated
- III. Degree of Wastewater Treatment
  - A. Primary
  - B. Secondary
    - 1. Activated
    - 2. Waste Activated
    - 3. Trickling filter humus
  - C. Advanced
  - D. Others
    - 1. Primary combined with waste activated sludge
    - 2. Primary combined with trickling filter humus
    - 3. Waste activated sludge combined with chemically precipitated sludge, etc.

The nature and characteristics of the sludges from industrial wastes are extremely diverse, when compared with municipal water and wastewater sludges. This study deals with the municipal sludges only,although the municipal wastewater treatment plant may receive both domestic and industrial wastewater.

The sludge produced from municipal water treatment plants are much different in character fromthose produced from wastewater treatment plants. In a municipal water treatment plant, sludge is obtained from two major sources: (1) sedimentation basins, and (2) filter backwashes. The specific character of this sludge depends upon the source of the raw water and the types of processes utilized.

SLUDGE QUANTITIES

The literature review did not reveal an exact value for the volume of the sludge being produced from municipal treatment plants throughout the U.S. However, several investigators have made attempts to estimate the sludge quantities. These estimates are rather fragmentary and, in some cases, conflicting. Nevertheless, these estimated values provide an order of magnitude value of the sludge quantities being generated throughout the U.S.

Wastewater Treatment Plant

The quantities of sludge generated from municipal wastewater treatment plants throughout the U.S. approach 120 lbs./capita/year or over 13 million tons/year, on a dry solids basis (5). The total volume of liquid wastes before treatment has been estimated to exceed 23 billion gallons/day (6) with the volume of the sludge produced from secondary treatment of the domestic wastewater alone being estimated to exceed 120 million gallons/day (7). Reported average values of the total digested sludge was 25 lbs./capita/year (8). Table 1 shows typical quantities of sludge produced by different treatment processes. Quantities of the sludge on a dry solids per capita basis are highly variable, since they depend on the type of unit process and unit operation applied in the treatment of wastewater. This variation in the quantities of sludge produced by different treatment processes is evident from Table 1.

Because of the growing concern and greater emphasis on the enhancement of water quality and the environment, more sophisticated processes and equipment will be used in wastewater treatments. This will probably result in a great increase in the quantity of the sludge generated. Also, more communities will be served by the wastewater utilities. It is reported (5), that over 170 million people in the U.S. are being served by municipal utilities. It is further estimated that this figure will increase at a rate of 2.25%/year for the next 10 years.

Water Treatment Plant

The quantities of the sludge produced in municipal water treatment plants are naturally far less than those produced from wastewater treatment plants. The controlling factor in the production of sludge at a municipal water treatment plant is the source of the raw water. Ground water supplies are normally high in hardness and frequently high in manganese, magnesium, and iron. Commonly, lime, lime-soda, or lime-caustic are used to soften such waters. The resulting sludge

TABLE 1: Normal Quantities of Sludge Produced by Different Treatment Processes* (14)

Treatment Process	Normal Quantity of Sludge						Dry Solids	
	Gal/ million gal of sewage	Tons/ million gal of sewage	Cu ft/ 1,000 persons daily	Moisture %	Specific gravity of sludge solids	Specific gravity of sludge	Lb/ million gal of sewage	Lb/ 1,000 persons daily
Primary sedimentation:								
Undigested	2.950	12.5	39.0	95	1.40	1.02	1.250	125
Digested in separate tanks	1,450	6.25	19.0	94	----	1.03	750	75
Digested and dewatered on sand beds	------	0.94	5.7	60	-----	----	750	75
Digested and dewatered on vacuum filters	------	1.36	4.3	72.5	-----	1.00	750	75
Trickling Filter	745	3.17	9.9	92.5	1.33	1.025	476	48
Chemical Precipitation	5,120	22.0	68.5	92.5	1.93	1.03	3,300	330
Dewatered on vacuum filters	------	6.0	19.3	72.5	-----	----	3.300	330
Primary sedimentation and activated sludge:								
Undigested	6,900	29.25	92.0	96	-----	1.02	2,340	234
Undigested and dewatered on vacuum filters	1,480	5.85	20.0	80	-----	0.95	2,340	234
Digested in separate tanks	2.700	11.67	36.0	94	-----	1.03	1,400	140
Digested and dewatered on sand beds	-----	1.75	18.0	60	-----	----	1,400	140
Digested and dewatered on vacuum filters	-----	3.5	11.7	80	-----	0.95	1,400	140
Activated sludge:								
Wet Sludge	19,400	75.0	258.0	98.5	1.25	1.005	2,250	225
Dewatered on vacuum filters	-----	5.62	19.0	80	-----	0.95	2,250	225
Dried by heat dryers	-----	1.17	3.0	4	-----	1.25	2,500	225
Septic tanks, digested	900	-----	12.0	90	1.40	1.04	810	81
Imhoff tanks, digested	500	-----	6.7	85	1.27	1.04	690	69

*Based on a sewage flow of 100 gpcd and 300 ppm, or 0.25 lb per capita daily, of suspended solids in sewage.

production is quite high, with an average of 2 tons/million gallons of water treated on a dry solids basis. Surface waters are generally low in hardness, but high in turbidity and microorganisms. Alum, chlorides of iron, and organic polymers, etc. are generally applied for coagulation, flocculation, and purification purposes. The quantities of the sludge produced are less, being approximately 0.16 ton/million gallons of water treated on a dry solids basis.

WASTEWATER TREATMENT PLANT SLUDGE CHARACTERISTICS

Wastewater treatment plant sludges have been defined as a mixture of solid phases suspended in an aqueous solution of dissolved substances. Characteristics of the sludges from wastewater treatment plant are highly variable, and depend on the sources of the wastewater, type of sewerage system, unit of operation and unit process to which both the wastewater and the sludge are subjected, and the degree of treatment required.

In general, primary sludge is gray in color, slimy in nature, and gives an offensive odor. It has a solids content ranging from 1 to 5% and is readily digested under suitable conditions of operation. The fresh solids include chemicals that have been used for flocculation and sedimentation, in more or less stoichiometric amounts, and up to 90% of the suspended solids present in the raw wastewater (10).

Activated sludge is generally brown in color. When the color darkens, it indicates septic conditions. The fresh sludge has an inoffensive characteristic odor. In septic conditions it has the disagreeable odor of putrefaction. Some general properties are presented in Table 2.

Trickling filter humus has a brownish color and is in the flocculated condition. When sludge is fresh, it has a relatively inoffensive odor; but when it undergoes decomposition, which is relatively slower than for other undigested sludges, it gives off a very offensive odor. The solids content of humus approaches 3% for high-rate filter and 7% for low-rate filters (11). The low-rate trickling filter captures from 50 to 60% of the dissolved solids reaching the filter; while for high-rate filter the percentage ranges from 80 to 90% (10).

Digested sludge has a dark-brown to black color. If the sludge is thoroughly digested it will not have an offensive odor; it has an odor similar to that of hot tar or burnt rubber. During drying, both moisture and entrapped gases are released, leaving a well-cracked surface, with an odor similar to that of garden loams. Some general properties of digested sludges are presented in Table 2.

The solids fraction of the wastewater sludge are primarily composed of biodegradable material, stable organic matter and inert material. The average reported proportions of these constituents are as follows (1):

TABLE 2: Some General Properties of Activated and Digested Sludge Investigated by Howe (15)

Digested Sludge	
Color	Brown
Physical State	Gelatinous mass or jelly-like
ph	7.0 - 9.0
Percent Solids, Total	0.2 - 4.0
Carbon Nitrogen Ratio	4.0 - 7.0
Density (gm/ml)	0.95 - 1.10
Ion Exchange Capacity (Milliequivalent per 100 gm solids)	350 ± of both cation and inion
O-R Potential (mv)	+ 100 to +450
Chemical Elements Found	C, N, H, O, P, K, S, Al, Ca, Mg, Cl, Na, Fe
Major Contents	Gelatinous matter of microbial matrix
Other Contents	Amino acids, vitamins, sugar, nitrate sulfate, phosphate, etc.

Activated Sludge	
Color	Blackish
Physical State	Amorphous, non-plastic and heterogenic mixture
ph	6.5 - 8.0
Percent Solids, Total	3.0 - 8.0
Carbon-Nitrogen Ratio	14.0 - 22.0
Density (gm/ml)	1.050 - 1.200
Cation Exchange Capacity (Milliequivalent per 100 gm solids)	300 - 450
O-R Potential (mv)	-400 to - 420
Chemical Elements Found	K, Cr, Zn, Sn, Mn Fe, Cu, Ca, Mg, Si, etc. Varied according to the origin of raw sludge
Major Contents	Humus-like and lignin-like material
Other Contents	Phosphates, sulfides, ammonium, biocarbonates, carbonates, organic acids, polyuronides, alcohols, etc.

Biodegradable organics	30%
Stable organics	35%
Inert material	35%

The physical condition and composition of the solid fraction for an average domestic sewage are presented in Table 3 (1).

General classification and significant characteristics for these sludges are presented in Table 4 (12). A schematic of those analyses which is most helpful in characterization of wastewater sludges is shown in Figure 1 (13).

The effective utilization of wastewater sludges will be dictated by six major physical and chemical properties. In order to properly describe the sludge characteristics these six properties, outlined below will be discussed in much greater detail: Settling Characteristics, Specific Resistance, Flow Characteristics, Calorific Values, Chemical Composition, and Fertilizer Values. Other characteristics not pertaining to this study include solids, pH, odor, oxygen demand, alkalinity, temperature, hexane solubles, etc.

Sludge Settling Characteristics

The settling characteristics of the sludge are vital parameters, since the main objective of the sludge treatment is to decrease the volume of the solid residue of the sludge. Based on the particle size concentration and, tendency for interaction, settling is divided into four types.

In type I settling, particles settle as an individual entity, and strong interaction force does not exist between the particles. This type of settling is called "discrete settling".

In type II settling, particles coalesce or form flocs during sedimentation. This coalescence increases the particle's mass which causes a faster settling rate. This is referred to as "flocculant settling".

In type III settling, intraparticular forces are strong enough to hinder the settling nature of the neighboring particles. Thus, particles remain in a fixed position with respect to each other and settle as a unit. A distinct interface between the solids and the liquid develops. This type of settling is referred to as "Zone Settling".

In type IV settling, the particles at the bottom of the tank are further compacted by the weight of the particles which are constantly being added. Thus, settling occurs only by compression of the structure or mass of the settled particles. This type of settling is known as "Compression Settling". It is very common that more than one type of settling will occur at a given period during sedimentation operation.

TABLE 3: Physical Condition and Composition of Solids in an Average Domestic Sewage (1)

(Numbers are in mg/1)

Total Solids 600	Suspended Solids 200	Settleable Solids 120	Organic 90 Inorganic 30	Settleable Solids 120	Total Solids 600
		Colloidal Solids 80	Organic 55 Inorganic 25	Colloidal Solids 120	
	Dissolved Solids 400	Colloidal Solids 40	Organic 30 Inorganic 10		
		Dissolved Solids 360	Organic 125 Inorganic 235	Dissolved Solids 360	

TABLE 4: General Categorization of Sludges (12)

Sludge Source	Unit Process Function	Significant Characteristics
Influent ss (primary sludge)	Collection and concentration of suspended material	Concentration of ss, inorganic constituents, organic constituents, specific gravity (settleability), and dewaterability.
Chemical Treatment Sludge	Coagulation, precipitation, and concentration of particulates	All of those mentioned above, effects of pH changes, and effect of treatment chemicals on subsequent processes or water use.
Waste Activated Sludge	Concentration, digestion, dewatering, heat drying, and combustion	Fraction of inert materials, amenability of organic fraction to digestion, heat value per unit weight of sludge, settleability, and dewaterability.
Effluent As	Filtration	Concentration of ss, biological activity in terms of oxygen demand, composition of effluent sludge in terms of nutrients, both organic and inorganic, and microbial analyses.

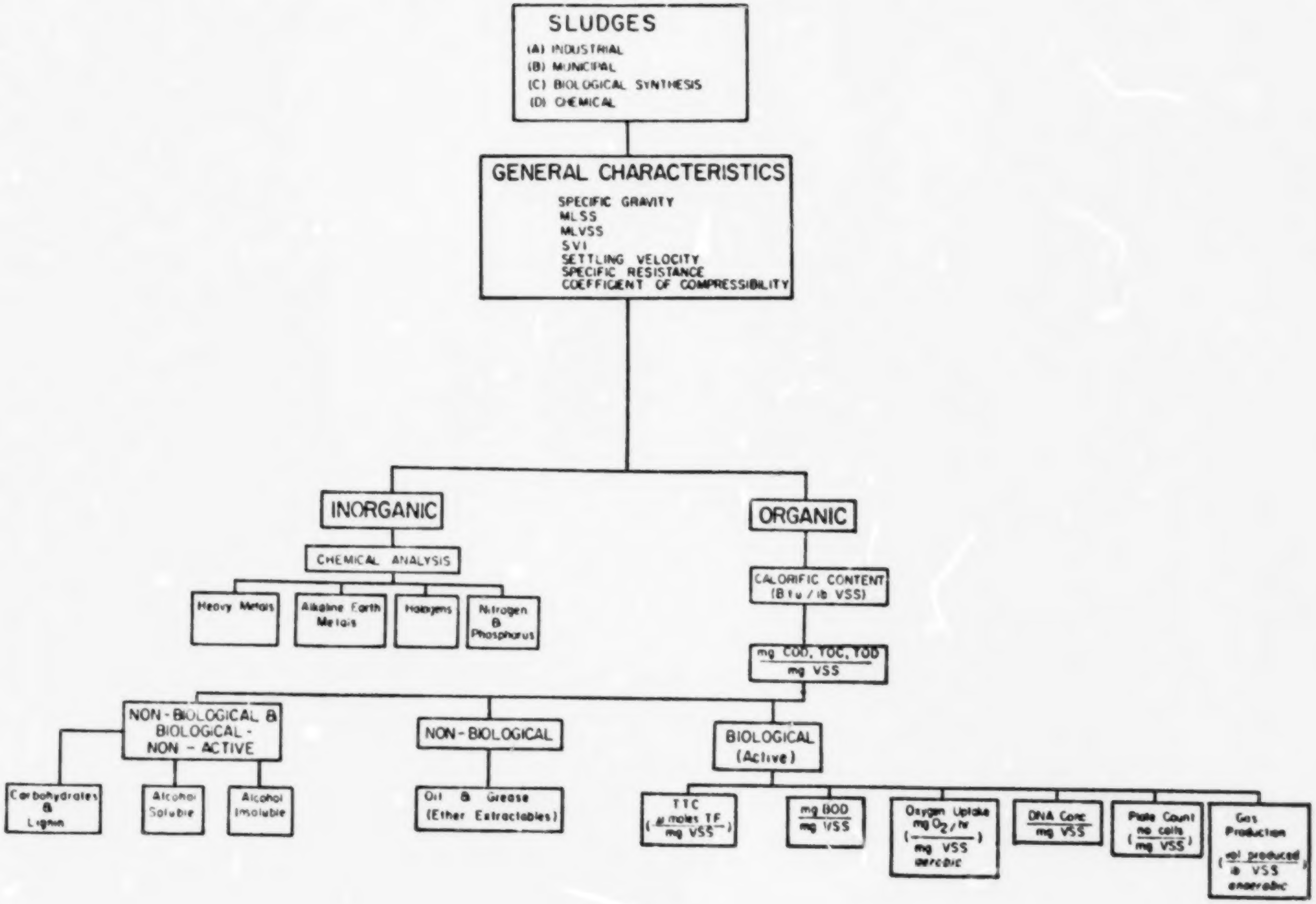
SLUDGES
(A) INDUSTRIAL
(B) MUNICIPAL
(C) BIOLOGICAL SYNTHESIS
(D) CHEMICAL
GENERAL CHARACTERISTICS
SPECIFIC GRAVITY
MLSS
MLVSS
SVI
SETTLING VELOCITY
SPECIFIC RESISTANCE
COEFFICIENT OF COMPRESSIBILITY
INORGANIC
CHEMICAL ANALYSIS
Heavy Metals
Alkaline Earth Metals
Halogens
Nitrogen & Phosphorus
ORGANIC
CALORIFIC CONTENT (Btu / lb VSS)
mg COD, TOC, TOD / mg VSS
NON-BIOLOGICAL & BIOLOGICAL - NON - ACTIVE
Carbohydrates & Lignin
Alcohol Soluble
Alcohol Insoluble
NON-BIOLOGICAL
Oil & Grease (Ether Extractables)
BIOLOGICAL (Active)
TTC (μ moles TF / mg VSS)
mg BOD / mg VSS
Oxygen Uptake (mg O2 / hr / mg VSS) aerobic
DNA Conc / mg VSS
Plate Count (no cells / mg VSS)
Gas Production (vol produced / lb VSS) anaerobic

Figure 1. Analysis of Wastewater Solids (13)

In the treatment of wastewater sludge, zone settling and compression settling are of major significance. Settling tests are usually required to determine the settling characteristics of the suspension. In the design of settling tanks, both clarification of the liquid over-flow and thickening of the sludge under-flow is involved. The over-flow rate for clarification requires that the average rise velocity of the liquid over-flowing the tank be less than the zone settling velocity of the suspension. Over-flow rate determination is based on such factors as are needed for free-settling and discrete-settling in the discrete-settling region (see Figure 2). These factors include the area needed on the basis of the rate of settling of the interface between the discrete-settling region and zone-settling region, and the rate of sludge withdrawal from the compression region. However, rate of zone settling seems to be the controlling factor because: (1) it is less than the rate of free particle settling, and (2) the upper portion of the sludge, just below the interface, acts as a filter to entrap and strain-out slower settling particles that otherwise might be carried out by the rising water through the sludge mass to the over-flow weirs (14).

The Talmadge and Fitch (16) method is generally applied to determine settling tank area requirement for zone settling. This method utilizes a settling column (1 liter graduated cylinder) filled with a homogeneous mixture of the sludge. The sludge solids are then allowed to settle under quiescent conditions. As the suspension settles, the position of the interface with respect to time is recorded. The settling curve is then plotted as shown in Figure 3. Tangents are projected from both hindered and compression settling zones. The point where the bisector of the angle formed by the two tangents intersects the settling curve, is called the point of critical compression or critical concentration "C_2". Furthermore, the height of the sludge in the settling column at the desired underflow concentration "C_u" is noted as H_u. This height can be determined using a mass-balance relationship:

$$H_o C_o = H_u C_u \qquad (1)$$

where,

H_o = initial height of interface in column,

C_o = initial concentration of the sludge.

To determine the settling time required to reach the desired underflow concentration "C_u", a horizontal line is drawn from the computed H_u value to a line tangent to the settling curve at the point of critical compression. The intersecting point represents the required settling time t_u.

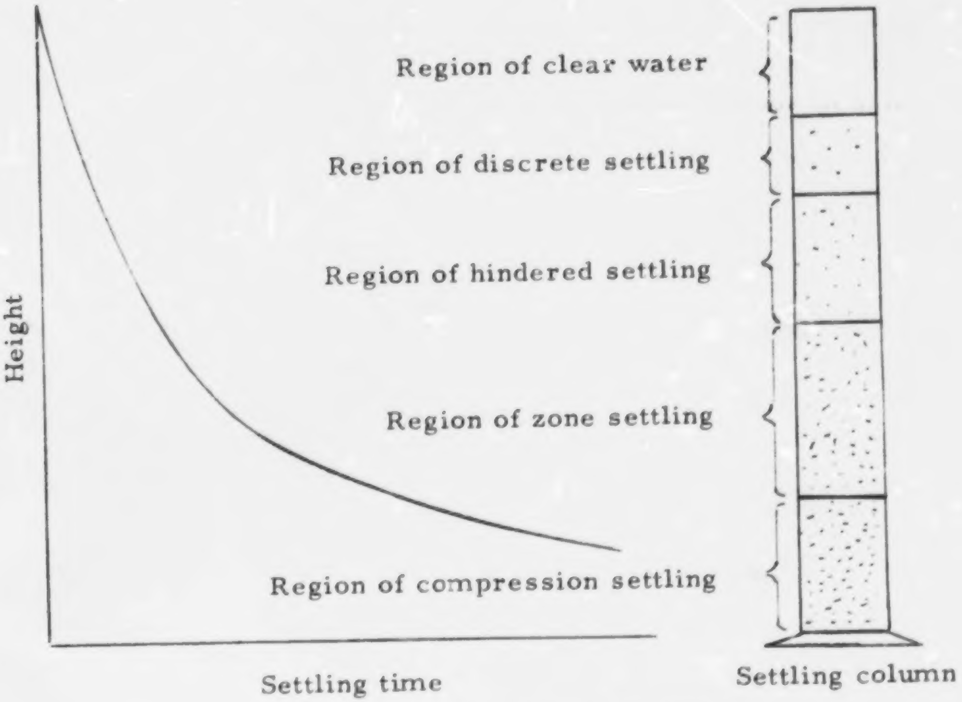
Height
Region of clear water
Region of discrete settling
Region of hindered settling
Region of zone settling
Region of compression settling
Settling time
Settling column

Figure 2. Schematic of Sludge Settling

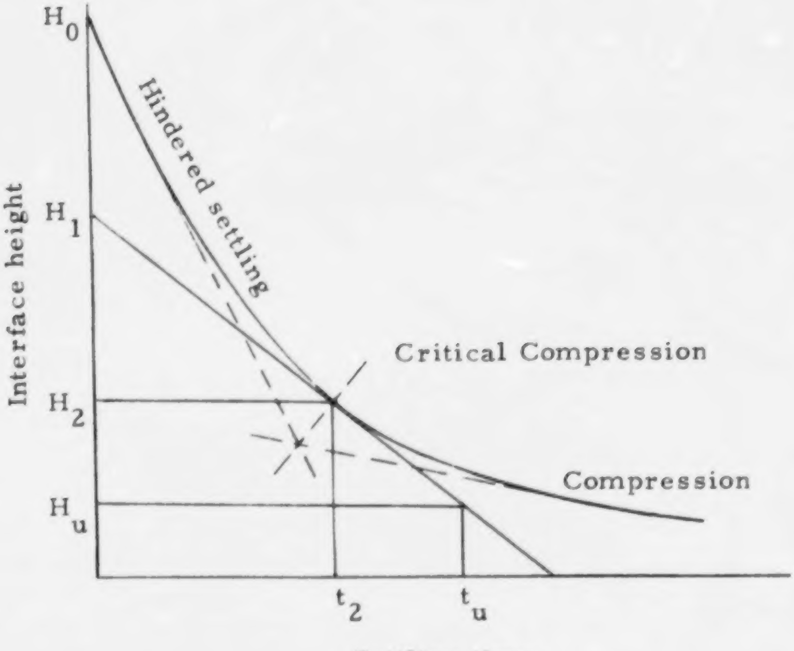
H_0
H_1
H_2
H_u
Interface height
Hindered settling
Critical Compression
Compression
t_2
t_u
Settling time

Figure 3. Graphical Presentation of Zone Settling Curve

The area required for sludge thickening is then found using the following relationship:

$$A = \frac{Q\,t_u}{H_o} \tag{2}$$

where,

A = area required for sludge thickening, sq. ft.,

Q = flow rate into tank, cfs,

H_o = initial height of interface in column, ft,

t_u = time to reach desired underflow concentration, sec.

The tank area required for clarification purposes is generally based on the underflow rate, i.e.,

$$A = \frac{Q}{OR} \tag{3}$$

and

$$OR = \frac{C_1}{U.A.\ C_o}\left(\frac{C_u - C_o}{C_u}\right) \tag{4}$$

where,

Q = flow rate into tank, MGD,

OR = overflow rate, gal/day/ft^2,

C_1 = 120, conversion factor from mg/l to lbs/gal,

$U.A.$ = unit area, ft^2/lb solid/day,

C_o = influent solids concentration,

C_u = underflow suspended solids concentration.

The concentration of the settled sludge is effected by a number of factors (17) which include: wastewater characteristics; type of biological treatment the wastewater receives and whether the sludge from biological treatment is handled separately, or is returned to the settling basin; design and operation of the settling tank; whether settling was promoted, using mechanical means or chemicals; settleable solids characteristics, density, shape percentage of volatile solids, viscosity, electrostatic charges; and solids concentration in the original suspension, sludge detention time, etc.

Settling rates of the bilogical sludge depend on the type of microorganism which is responsible for the nature of the substrate and organic loading in case of an activated sludge aeration basin. Further limitation of the settling rate parameters as noted by Ford (12) are as follows: (1) the effect of initial sludge depth on settling velocity; (2) stirring speed and configuration of racking mechanism; (3) lack of reproducibility when measuring sludge settleability in test cylinders, and (4) the effect of test-cylinder diameter on settling rates.

Larson (59) has carried out a series of tests, using various concentrations of similar sludge in different sizes of cylinders and has measured the settling rates. Results of his tests are graphically represented in Figure (4). It is apparent that for normal mixed liquorsolids concentrations applied in activated sludge systems, the smaller the test cylinder size (large circumference/area ratio) the higher would be the settling velocity of the solids.

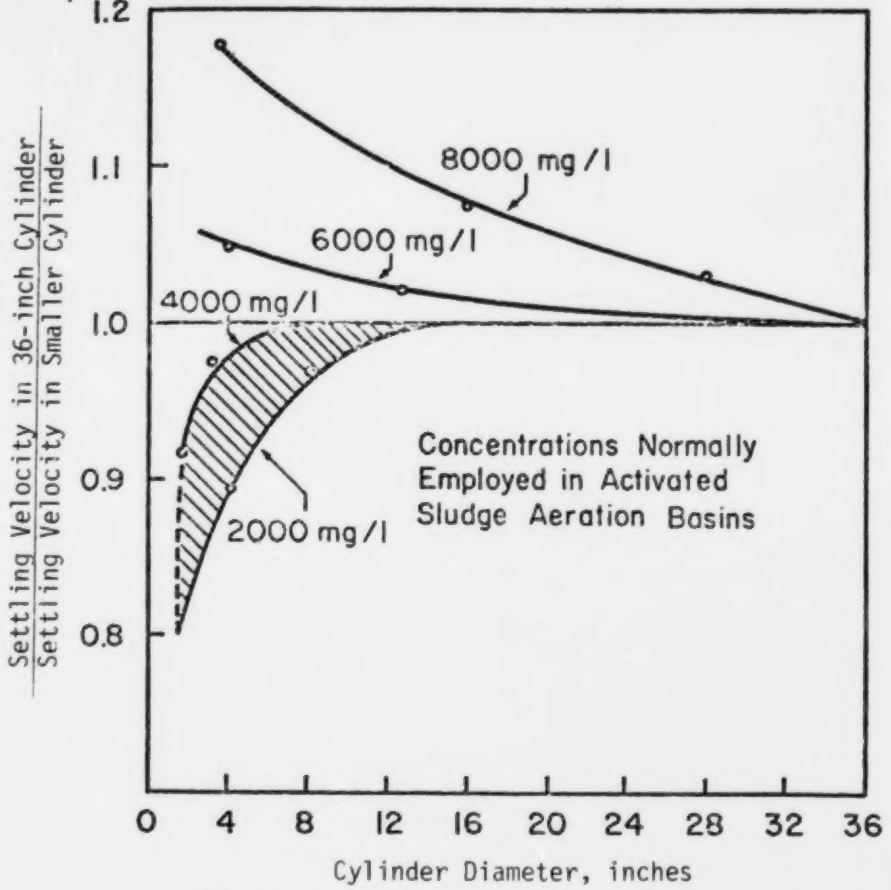

Figure 4. Effect of test cylinder diameter on sludge settling rate (59)

Heat treatment of sludge under pressure for one hour at temperatures below 250°F has been shown to improve settling characteristics of the sludge significantly. Substantial solids volume reduction, and sludge solids concentration have been observed. Results of the study made by Hurwitz et al., (19) on three types of sludges listed in Table 5, are given in Figure 5 and Figure 6.

Table 5. Sewage Sludge Characteristics (19)

Sludge Designation			
Type of Sludge	Raw Primary	Digested Primary Activated	Raw Activated
Total Solids Concentration - g/l	49.7	61.3	23.0
Ash-g/l	10.4	26.0	8.6
Volatile-g/l	39.3	35.3	14.4
% Volatile Solids	79.0	57.6	62.5
COD-g/l	61.8	57.6	31.3
COD/Volatile Ratio	1.57	1.64	2.17

The concentration of solids in sludges as a result of treatment has been reported in the literature and is summarized in Table 6. These values indicate that the solids content of sludge varies from 0.5 to 10% for raw sludges, and from 2 to 15% after digestion. Digested sludge shows a definite thickening when the solids content is higher than 5%. It develops the consistency of syrup and is less free flowing compared to water. At a solids content of 15 to 20% the sludge will no longer flow, and it can be handled with a spading fork at solids content of 25%. At 50% solids content the sludge appears moisture free and at 90% concentration it is dust dry.

Specific Resistance of Sludge

Another important physical characteristic of the sludge in the design of treatment processes is the specific resistance; the difficulty encountered in removing water or conversely the ability of the sludge to retain water. Some of the processes where specific resistance is important are vacuum filtration; centrifugation; and drying on sand beds (1).

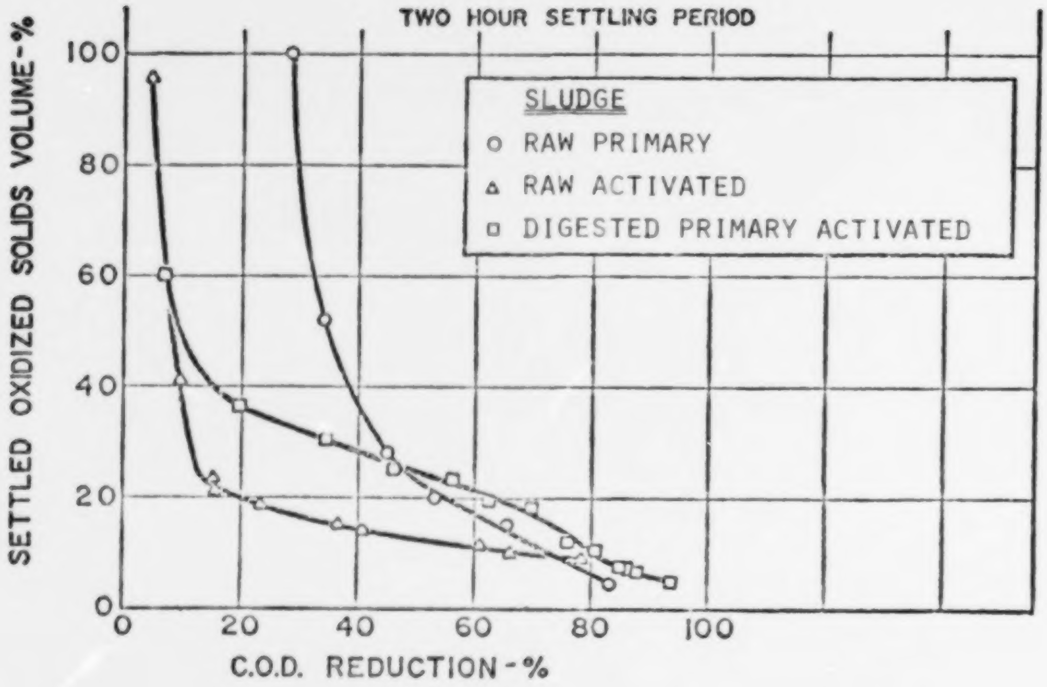

Figure 5
COD reduction vs. settled oxidized solids volume(19)

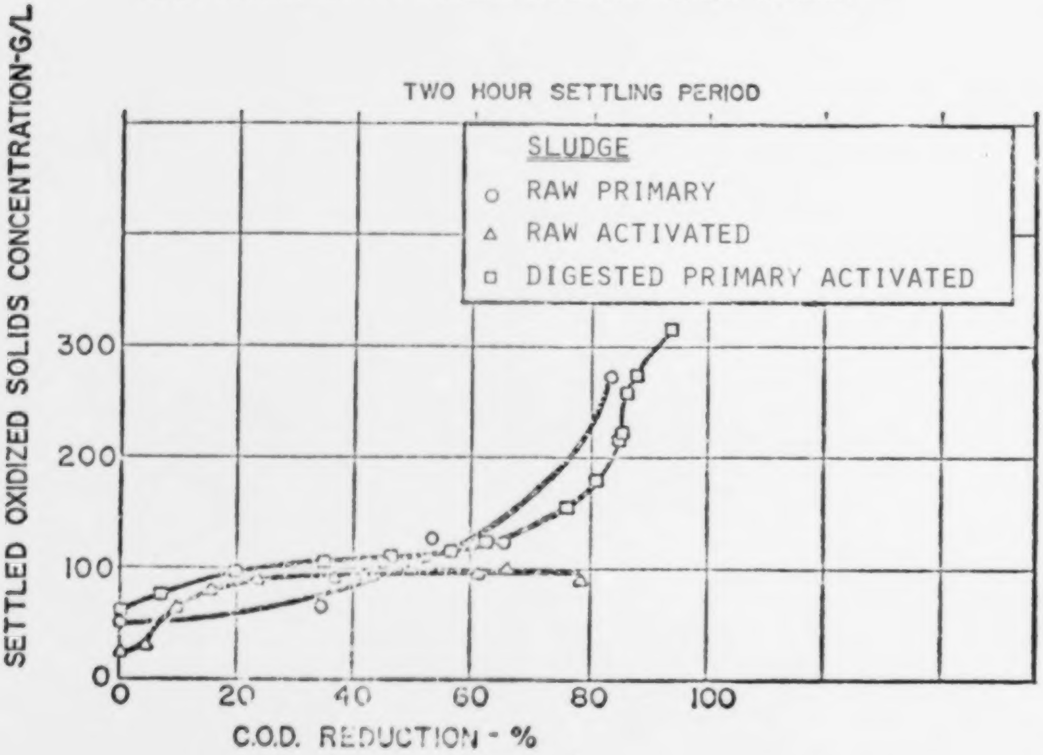

Figure 6
Settled oxidized solids concentration vs. COD reduction(19)

Table 6. Solids Concentration of Sludges

Type	Solids Conc. (14,18,33
Raw Sludge	
Plain Sedimentation	2.5 - 5.5%
Trickling Filter	4 - 10%
Trickling Filter, Mixed	3 - 6%
Activated	0.5 - 1.2%
Activated, Thickened	1 - 2%
Activated, Mixed	2.6 - 5%
Modified Aeration	2 - 4%
Modified Aeration, Mixed	3 - 4%
Digested Sludge	
Plain Sedimentation	10 - 15%
Trickling Filter	10% -
Activated	2 - 3%
Activated, Mixed	6 - 8%

The specific resistance "r" concept is used to evaluate filtration characteristics of the sludge. Specific resistance is numerically equal to the pressure difference required to produce a unit rate of filtrate flow of unit viscosity through a unit weight of cake (20,21). Studies on the theoretical approach to filtration go back to 1908, to Hatschek (60); and, reached a satisfactory stage by Ruth et al., (61,62) and Carman (63,64) in 1933-1935. However, the application of these theories and selection of the best method for filtration of sewage sludge was made by Coakley and Jones (22) in 1956. They have found that among all of the filtration theories available, the simplest and most easily applicable theory is that of Carman's.

Carman's basic equation for a rigid cake is:

$$\frac{dv}{dt} = \frac{PA^2}{\theta(rivV + RA)} \qquad (5)$$

where,

$\frac{dv}{dt}$ = rate of flow of liquid across the bed thickness,

P = pressure difference across the bed,

A = area of the bed,

μ = viscosity of the filtrate,

v = constant of proportionality between volume of filtrate and volume of solids deposited,

V = volume of filtrate,

R = initial resistance per unit area for a liquid of unit viscosity.

r_i = the resistance of the unit weight of cake per unit area,

Integrating, e. g., at constant pressure we will have:

$$t = \frac{\mu r_i v}{2PA^2} V^2 + \frac{\mu R}{PA} V \qquad (6)$$

or

$$t/V = \frac{\mu r_i v}{2PA^2} V + \frac{\mu R}{PA} \qquad (7)$$

This equation gives a straight line when t/v is plotted against V with a slope b equal to:

$$b = \frac{\mu r_i v}{2PA^2} \qquad (8)$$

and the specific resistance is obtained by simple rearrangements, i. e.,

$$r_i = \frac{2PA^2}{\mu v} b \qquad (9)$$

Coakley and Jones determined that Carman's filtration theory for rigid cake is also applicable for compressible cakes like those obtained from sewage sludge, if "r_i is regarded as a function of "P". They have also noted that it is easier to express the sludge concentration by weight of dry cake solids per unit volume and liquid, C, than by unit volume of cake per unit volume of filtrate, v. Substituting C for v in equation 9, the relationship for "r" applicable to sewage sludges, was developed, i. e.,

$$r = \frac{2bA^2P}{\mu C}, \qquad (10)$$

and

$$C = \frac{1}{\frac{C_i}{100 - C_i} - \frac{C_f}{1\text{--} - C_f}} \qquad (11)$$

where,

P = pressure difference across the cake, gr/cm^2,

A = area of filtering surface, cm^2,

μ = viscosity of filtrate, poise,

r = specific resistance, as resistance per cm^3 of cake, sec^2/gr,

b = slope of the t/v vs. V plot,

V = volume of filtration,

t = time interval during test,

C_i = the percent liquid of the sludge,

C_f = the percent liquid of the filter cake.

It was further suggested that in any experimental determination of specific resistance, t and V should not be measured from the beginning of the filtration. It is necessary to record the filtrated volume after a thickness of cake having a resistance equal to the resistance of the filter cloth has been deposited. This problem is normally over come if the first two minutes of the test are neglected.

The specific resistance "r" is also a function of the pressure difference in accordance with the relationship:

$$r = r' P^s, \qquad (12)$$

where,

r' = specific resistance at unit pressure,

P = pressure difference of filtration apparatus,

s = coefficient of compressibility.

Typical values of coefficient of compressibility reported (22) for various types of sludges are:

Type of Sludge	Coefficient of Compress.
Digested	0.70 to 0.86
Activated	0.60 to 0.79
Raw	0.87
Humus	0.80

The parameters "r" and "s" indicate the dewatering abilities of the sludge. Low "r" values are indicative of a sludge with rapid draining or filtering characteristics and the reverse is true for high values of "r"(19). Typical values of "r" for various types of sludges are listed in Table 7.

Specific resistivity of sludge can be improved dramatically by using chemical coagulants. Among the most common chemicals used are trivalent metal ions such as Al^{+++} and Fe^{+++}; and organic polyelectrolytes (cationic, nonionic, anionic). A comprehensive study of chemical flocculants has been made by Tenney et al. (23)

The draining or filtering characteristics of the sludge can be significantly improved by employing a wet-air oxidation process (heat treatment at below 300 psi pressure and up to 300°F temperature). In this process, insoluble organic matter is converted to simpler, soluble organic compounds which are then oxidized and converted to CO_2 and water. It has been reported(19) that small amounts of oxidation, 15-20%, will convert the solid structure of the sludge from a hydrophilic nature to an easily drained or hydrophobic structure. Results of the effect of heat treatment for one hour on filtering characteristics of various sludges are illustrated in Table 8.

Sludge Flow Characteristics

In a wastewater treatment plant the solids which have been removed through various processes are hydraulically transported by pipeline. The densities of these solid particles are generally higher than the transporting fluid and in order to prevent the settling of these particles, a continuous mixing of the flow is essential (high turbulence).

TABLE 7

Reported Sludge Specific Resistance Values*(12)

Description	Stage	Specific Resistance ($sec^2/gram$) x 10^7
Domestic Activated Sludge		2,800.0
Activated (digested)		800.0
Primary (raw)		1,310-2,110
Primary (digested)		380-2,170
Detention Time	**Stage**	
7.5 days	1	1,590.0
10.0 days	1	1,540.0
15.0 days	1	1,230.0
20.0 days	1	530.0
30.0 days	1	760.0
15.0 days	2	400.0
20.0 days	2	400.0
30.0 days	2	480.0
Activated sludge + 13.5% $FeCl_3$		45.0
Activated sludge + 10.0% $FeCl_3$		75.0
Activated sludge + 125% by wt. newsprint		15.0
Activated digested sludge + 6% $FeCl_3$ + 10% CaO		5.0
Activated digested sludge + 125% by wt. newsprint + 5% CaO		4.5

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* All values at 500 gms/cm^2 pressure

TABLE 8

Specific Resistance Values of Oxidized Sludges(19)

Raw Primary Sludge

Oxidation Temperature, °F		100	150	180	190	200	210	220	250
%COD Reduction	Untreated	0.0 heated	19.3	28.2	34.2	45.1	53.1	65.7	83.4
Specific Filtration Resistance $sec^2/g \times 10^7$	500-800	800	26	3.1	4.7	5.2	4.2	9.4	4.3

Digested Primary-Activated Sludge

Oxidation Temperature, °F		120	160	170	180	190	200	210	220	230	240
%COD Reduction	Untreated	6.9	19.5	34.8	46.3	56.4	62.5	69.9	76.0	80.7	84.9
Specific Filtration Resistance $sec^2/g \times 10^7$	2,170	91	3.5	5.2	6.7	6.6	6.7	10.1	8.6	8.8	4.2

Raw Activated Sludge

Oxidation Temperature, °F		150	170	180	190	220	260
%COD Reduction	Untreated	9.5	15.4	23.3	39.3	63.7	78.3
Specific Filtration $sec^2/g \times 10^7$	18,700	58	14.1	14.6	11.5	10.9	6.6

The heterogeneous nature of wastewater sludge causes flow phenomena. Thus, direct application of existing hydraulic formulas for head loss computation is not adequate in most cases. Although sludge flow is affected by a number of factors, the most significant one is the moisture content (M) of the sludge. Based on the moisture content, the sludge flow is classified by: (1) flow in suspension, and (2) plastic flow.

The moisture content which delineates between the two types of flow is called the limiting moisture content (M_L) and is defined as the critical moisture content in percent, where a measurable yield value (S_y) first occurs. Thus, below M_L the flow is plastic and above M_L it is in suspension. The major parameters which have to be considered in the study of sludge flow are as follows: (1) Reynolds Number (R_N) and critical velocity; (2) specific gravity; (3) coefficient of rigidity; and (4) head loss.

In the case of flow in suspension, the presence of suspended particles has a negligible effect on the viscosity of the liquid. Thus, the characteristics of the sludge flow are very close to that of viscous liquids, and the head loss is independent of M. The Reynolds number, R_N, can be expressed by the relationship (24):

$$R_N = \frac{\rho VD}{\eta} \rightarrow \frac{\rho VD}{\mu} \qquad (13)$$

where,

ρ = density of the fluid, lbs. - sec.^{2}/ft^4,
V = flow velocity, ft/sec.,
D = pipe diameter, ft,
η = coefficient of rigidity, lbs. - sec./ft^2
μ = coefficient of viscosity, lbs. - sec./ft^2.

The suggested lower and upper values for R_N are 2000 and 3000, respectively(25). Thus, the critical velocities are:

$$V_{cl} = \frac{2000\mu}{\rho D} \qquad (14)$$

and

$$V_{cu} = \frac{3000\mu}{\rho D} \qquad (16)$$

and the Reynolds number becomes,

$$R_N = \frac{\rho VD}{\mu} = \frac{3\rho DV^2}{3\eta V + 16 S_y D} \tag{17}$$

The critical velocities are

$$V_{1c} = \frac{1000\eta + 103\sqrt{94\eta^2 + D^2 S_y \rho}}{\rho D} \tag{18}$$

and

$$V_{uc} = \frac{1500\eta + 127\sqrt{140\eta^2 + D^2 S_y \rho}}{\rho D} \tag{19}$$

From Table I it can be seen that the specific gravity for the various typed sludges does not vary significantly. The margin of variation is only 7% (24). The specific gravity value for a sludge can be used to determine its specific weight from the relationship, $\rho = 62.4\ G$.

The coefficient of rigidity of sludge is a direct function of the sludge moisture content. The correlation between moisture content and coefficient of rigidity is shown in Figure 7.

"High" and "Mean" values are offered for design purposes. However, as Chou (24) states, "The experimental determination of η by either viscometer or from pressure drop measurement is very delicate". Thus, any over estimate will increase the critical velocity and to some extent the head loss.

Head loss of the sludge flow in pipelines depends on such factors as type and stage of flow. When sludge flow is typified by flow in suspension and the velocity of the flow is in the laminar stage, head loss is practically the same as that for water, i. e.,

$$h_1 = \frac{L\eta V}{\rho D^2} + \frac{L\mu V}{\rho D^2} \tag{20}$$

where,

h_1 = head loss between any two points in a pipeline, ft.,

L = distance between two points in a pipeline, ft.

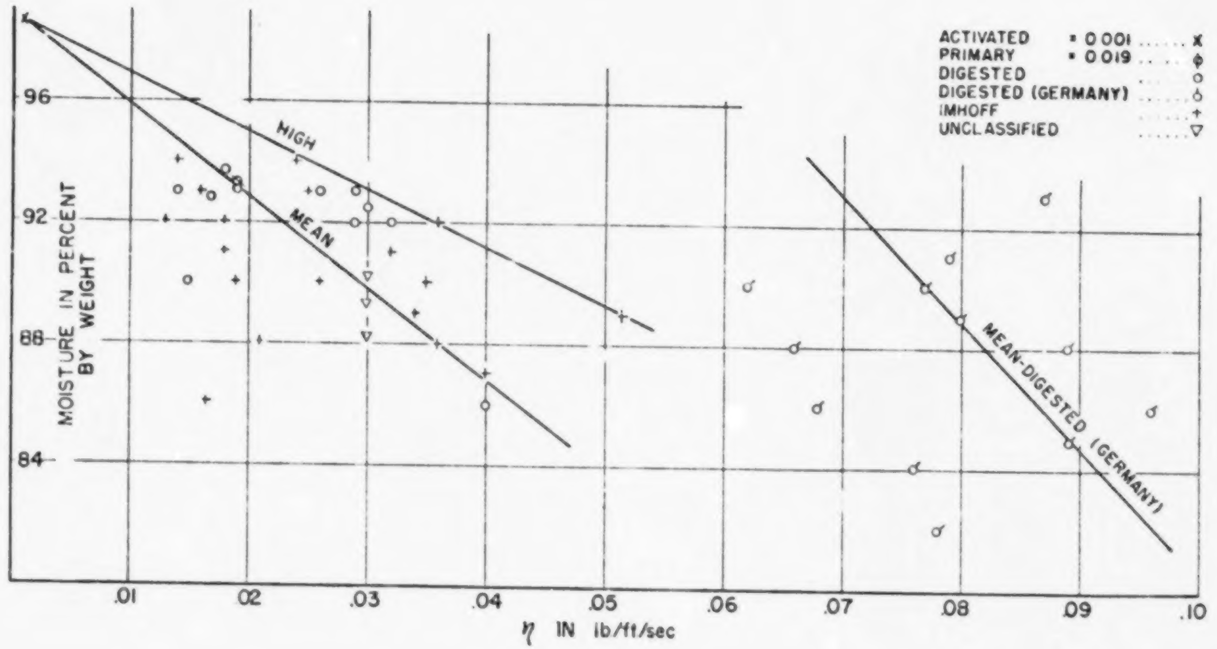


Figure 7. Coefficient of Rigidity η of Sludges$^{(24)}$

When the velocity of the flow is turbulent, the head loss can be computed by the relation:

$$h_s = G^2 hw, \qquad (21)$$

where,

h_s = head loss of flow in suspension with moisture content M, ft.

hw = corresponding head loss of water, ft.,

G = specific gravity of sludge.

Laminar plastic flow is the most common type of sludge flow and the suggested formulas for determining the head loss are (25):

Sludge Head $$\frac{h_l}{L} = \frac{16S_y}{3\ D} + \frac{V}{D^2} \qquad (22)$$

Water Head $$\frac{h_l}{L} = \frac{16S_y}{3WD} + \frac{\mu V}{WD^2} \qquad (23)$$

The literature offers no specific formulas for computing the head loss for plastic flow where turbulent conditions prevail. Available information is rather inconsistent and in some cases contradictory. Some studies have shown that head loss is a function of M and varies from 1.5 to 8 times that of water. Other studies claim that the head loss is independent of M and is almost the same as that of water (24). The most reliable information appears to be from the work of Brisbin (26) and Chou (27).

Calorific Values of Sludges

Calorific values of the sludge is a vital parameter in the design and operation of incinerators for the disposal of sludges. Calorific values of the sludge, combined with its ultimate analysis, determine the quality of the sludge for incineration. Reported (28) values indicate that the combustible fraction of the sludge is variable although a large portion is grease. Raw sludge has been found to contain 75% combustible matter, and digested sludge may contain only 50% combustible matter on an average basis. Available information on calorific values of various sludge has been collected and is listed in Table 9. As seen from Table 9 the heat content varies from 5000 to 14000 Bt u's per pound on a dry basis. The

TABLE 9

Calorific Values of Various Sludges

Description	% Combustible	% Ash	Btu/lb	Ref.
Undigested Sludge	71.5	28.5	13,900	40
	72.6	27.4	12,320	40
	79.9	20.3	11,775	40
	71.7	28.3	11,335	40
	80.0	20.6	11,420	12,29
	74.0	26.0	10,285	41
Digested Sludge	48.3	51.7	9,825	40
	52.5	47.5	9,500	40
	59.6	40.4	8,980	40
	49.6	50.4	8,020	40
	48.0	52.0	10,750	40
	59.6	40.4	5,290	12,29
Grease and Skimmings	88.5	11.5	16,750	40
Screenings	80.2	19.8	10,350	40
	74.8	25.2	10,000	40
	92.0	8.0	10,000	40
	84.4	15.6	9,950	40
	86.4	13.6	8,980	40
Grit	33.2	69.8	10,146	40
	33.2	69.8	4,000	12,29
Activated Sludge	----	----	6,540	41
Sludge Digester Gases	----	----	650	42

calorific value of the sludge will increase dramatically if organic polymers are employed in conditioning the sludge. It is believed that an increase from 1500 to 4000 Btu's/lb of dry solids, and ash content reductions of 5 to 20% can be obtained using organic polymers (29).

The heat value of the sludge can be determined if the chemical analysis of the sludge is known, using DuLong's equation,

$$Q = 14,600\ C + 62,000\ (H - \frac{O}{8}) \qquad (24)$$

where,

Q = Btu/lb

C = % Carbon

H = % Hydrogen

O = % Oxygen

Typical values for the ultimate analysis and calorific values of the sludge and other waste materials are presented in Table 10.

Chemical Composition of Sludge

A proper assessment of the usefulness of the sludge can be made if the chemical composition is known. A compilation of the organic fractions for the various sludges reported in the literature is presented in Table 11. Analysis of the specific organic constituents of a sludge is important in predicting what conditions will prevail during dewatering and also helps in determining what specific effects the sludge might have on solid characteristics.

TABLE 10: Ultimate Analysis of Waste Materials (28)

Material	C%	H%	O%	N%	Btu/lb
Wood	53.5	6.0	40.4	0.1	9,900
Garbage	54.5	7.5	35.0	1.0	10,000
Rubbish	53.0	6.0	37.0	3.5	9,000
Sludge	55.0	7.0	35.0	3.0	10,000

Hunter and Heukelekian (30) have made a comprehensive investigation of the composition of various sewage fractions. They found that the particulate-fraction solids were about 80% organic matter, while the soluble-fraction solids contained about 30% organic matter. The particulate-fraction solids

TABLE 11: Organic Fractions for Various Sludges

(Percent of Dry Weight) (12)

Constituents	Plain Settled	Digested	Activated	Raw Activated	15% [t] Oxidized	80% [t] Oxidized
Organic matter	60 - 80	45 - 60	62 - 75	67.0	64.0	23.4
Total Ash	20 - 40	40 - 55	25 - 38	33.0	36.0	----
Pentosams	1.00	1.6	2.1	7.2	2.4	0.0
Grease and Fat [**]	7-35	3 - 17	5 - 12	21.0	19.3	1.8
Hemicellulose	3.20	1.6	-------	-----	----	----
Cellulose	3.80	0.6	7.0	-----	----	----
Lignin	5.80	8.4	-------	-----	----	----
Protein	22 - 28	16 - 41	32 - 41	12.4	8.4	0.5

[**] Ether extract

[t] Solids fraction only

contained from 4 to 7% organic nitrogen, while the soluble-fraction solids contained less than 1%. The particulate fraction was composed mainly of carbohydrates, 24%, amino acids, 19%, and grease, 17%, and free fatty acids were present only in small amounts. The soluble organic matter was found to be composed largely of ethyl-ether extractable matter, of which the organic acids were the primary constituents, 56%.

A study made by Hunter and Rickert (31) showed that activated sludge treatment resulted in the following solids reduction: (a) total solids were reduced 42% and volatile solids 66%; (b) particulate total solids were reduced 86% and particulate volatile solids 86%; and (c) soluble total solids were reduced 20% and soluble volatile solids 46%. This study also showed that activated sludge treatment is very effective in reducing particulate organic matter but ineffective in reducing soluble organic matter. However, the author and others believe that they may have had an atypical substrate and system, particularly in reference to their results showing the ineffectiveness of an activated sludge process in reducing soluble organic matter.

The organic content of sewage sludge is usually measured from the BOD and the volatile solids determination. However, in recent years the trend is to use other means so that the chance that inorganics might also volatilize during the course of the experiment is eliminated. More useful and implicit tools for determining the organic content are the COD and the TOC tests.

Rudolfs (32) has made a thorough analysis of the inorganic constituents of digested and activated sludges. The results of his investigation are listed in Table 12. A comprehensive investigation of the metallic content of the various air-dried sludges were made by Thompson et al.(8). Results of their studies are presented in Table 13. A more or less complete list of minor and major elements found in the various types of sewage sludge is presented in Table 14.

Fertilizer Value of Sludge

Disposal of wastewater treatment stabilized sludges in either the liquid or dried solid form, as soil fertilizer has received significant attention in the U. S. because of the high cost and environmental effects of alternate means of disposal.

TABLE 12

Inorganic Constituents in Sludges

(Percent of Dry Weight) (32)

Chemical Constituents	Chemical Symbol	Digested Sludge (Toledo) (%)	Activated Sludge (Milwaukee) (%)
Silicon	SiO_2	15.60	8.45200
Iron	Fe_2O_3	5.43	7.14800
Aluminum	Al_2O_3	6.80	3.21100
Calcium	CaO	6.64	1.67500
Magnesium	MgO	1.83	1.81000
Potassium	K_2O	0.42	0.86200
Sodium	Na_2O	-----	0.98800
Titanium	TiO_2	-----	0.08300
Manganese	MnO	0.78	0.32700
Copper	CuO	1.00	0.46500
Barium	BaO	0.06	0.06110
Zinc ZnO	ZnO	1.24	0.01627
Lead	PbO	0.81	0.22500
Nickel	NiO	----	0.00561
Cobalt	CoO	----	0.00020
Sulfur	SO_3	8.12	2.90000
Chlorine	Cl_2	----	0.50100
Chromium	Cr_2O_3	0.37	0.21900
Arsenic	As_2O_3	0.13	0.01347
Boron	B_2O_3	----	0.00426
Iodine	I	----	0.01130
Phosphorus	P_2O_5	2.02	3.08900
Ignition Loss	----	44.40	68.55000
TOTAL		95.55	99.90360

TABLE 13

Spectrographic Analysis for Metals Content of Air-Dried Sewage Sludge (As Percent of Air-Dried Sludge)(8)

Elements	Nichols Hills (1.)	Okla. City Northside No. 1 (2.)	Okla. City Northside No. 2 (2.)	Okla. City Southside (3.)	Broken Bow (4.)	Idabel (5.)	Norman No. 1 (6.)	Norman No. 2 (6.)	Holdenville (7.)	Hugo (1.)	Lawton (1.)	Enid (2.)
MAJOR												
Aluminum	Major	Major	Major	Major	Major	Major	Major	Major	Minor	Major	Major	Major
Calcium	Major	Major	Major	Major	1.30	Major	Minor	3.00	1.00	Minor	Minor	Major
Iron	2.00	2.00	2.00	1.30	2.00	2.00	1.50	1.50	2.00	2.00	2.00	2.00
Magnesium	1.00	1.50	1.00	1.50	1.00	1.00	1.30	1.30	0.10	0.50	1.00	1.00
Silicon	Major	Major	Major	Minor	Major	Major	Major	Major	Minor	Major	Major	Major
Titanium	1.50 to 2.00	1.50 to 2.00	1.50 to 2.00	1.00 to 1.50	1.50 to 2.00	1.50 to 2.00	1.50 to 2.00	1.50 to 2.00	0.10	1.00 to 2.00	0.50	0.70
INTERMEDIATE												
Barium	0.30	0.30	0.30	0.30	0.30	0.50	0.70	0.10	0.01	0.10	0.10	0.50
Copper	0.50	0.30	0.30	0.60	0.10	0.08	0.20	0.20	0.10	0.10	0.10 to 0.20	0.50
Manganese	0.10 +	0.10 +	0.10 +	0.10	0.07	0.09	0.10	0.10	0.01	0.10	0.05	0.10
Sodium	0.05	0.07	0.05	1.00	0.10	0.10	1.00	1.00	0.20	0.20	1.00	0.70
Nickel	0.08	0.05	0.05	0.30	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Tin	0.10	0.10	0.06	0.20	0.05	0.05	0.07	0.06	0.05	0.05	0.10	0.10
Vanadium	1.50	0.10	0.10	0.10	0.07	0.20	1.00	1.00	0.05	0.05	0.03	0.07
Zinc	0.30	0.50	0.50	0.70	0.50	0.70	0.70	0.70	0.50	0.50	0.30	0.30
Silver	0.01	0.01	0.01	0.10	0.01	0.01	0.01	0.01	0.05	0.05	0.01	0.03
Zirconium	0.05	0.05	0.05	0.05	1.00	1.50	0.50	0.10	0.01	0.01	0.03	0.05
TRACE												
Boron	0.01	0.01	0.01	0.007	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Beryllium	—	—	—	—	—	—	—	—	—	—	T	T
Chromium	0.06	0.01	0.01	0.10	0.01	0.01	0.01	0.01	T	T	T	0.03
Cobalt	0.01	0.05	0.05	—	T	T	—	—	—	0.005	0.005	0.01
Gallium	0.01	0.01	0.01	T	0.005	0.005	0.005	0.005	0.005	0.005	0.003	0.001
Molybdenum	0.007	0.007	0.005	0.10	0.01	0.01	0.01	0.01	T	T	0.03	0.03
Yttrium	T	T	T	—	T	T	T	T	—	T	T	T
Ytterbium	T	T	T	—	—	—	—	—	—	—	—	T
ASH CONTENT (%)	45.70	19.30	54.50	17.00	76.00	66.00	59.00	64.00	65.20	63.20	43.01	54.50

(1.) Primary settling, standard-rate trickling filter, final settling, separate sludge digestion.
(2.) Primary settling, activated sludge, final settling, separate sludge digestion.
(3.) Primary settling, two-stage filtration, final settling, separate sludge digestion.
(4.) Clarigester, standard-rate high-rate trickling filter, final settling.
(5.) Primary settling, standard-rate trickling filter, separate sludge digestion.
(6.) Biosorption, final settling, separate sludge digestion.
(7.) Imhoff tank, standard-rate fixed-nozzle filter, final settling.

TABLE 14

Summary of Major and Minor Elements in Sludge

(Milligram per Gram Dried Sludge) (34)

Elemental Analysis	Primary Sludge			Activated Sludge			Digested Sludge		
	Average	Range	No. in Sample	Average	Range	No. in Sample	Average	Range	No. in Sample
Al	5.10	10.78-1.83	3	10.0	17.0-4.35	3	17.86	36-7.75	4
Sb							0.897	0.984-0.81	2
As	1.24	1.49 0.83	3	1.20	22.22-0.101	3			
Ba	2.25	5.0-0.11	11	1.15	3.0-0.22	4	1.36	4.01-0.10	15
Be	0.0025	0.0030-0.0017	3	0.0035	0.0044-0.0026	2	0.0025	0.0065-0.0012	11
B	0.104	0.15-0.07	11	0.070	0.22-0.006	9	0.046	0.149-0.003	17
Cd	0.188	0.30-0.0034	4	0.35	0.44-0.26	2	0.264	0.50-0.001	10
Ca				13.0	18.0-9.0	7	33.5	112.0-4.9	15
Cr	2.05	9.0-0.08	15	4.31	17.0-0.1	8	2.28	11.0-0.10	28
Co	0.217	0.5-0.05	6	0.0016	0.0016	1			
Cu	2.00	6.0-0.0083	17	1.10	2.6-0.372	13	1.65	16.0-0.10	39
Fe	16.1	20.0-2.86	12	40.5	96.6-4.83	9	30.65	60.0-10.09	19
Pb	1.01	2.14-0.33	3	1.52	2.09-0.51	3	1.89	7.52-0.18	18
Mg	10.6	15.0-5.0	8	7.04	10.9-3.01	7	7.49	13.0-1.0	17
Mn	0.781	1.0-0.16	11	0.310	0.93-0.055	9	0.976	6.04-0.06	17
Hg	0.0046	0.006-0.0030	2	0.016	0.020-0.012	2			
Mo	0.362	1.0-0.05	11	0.197	0.89-0.006	8	0.254	1.29-0.002	24
Ni	0.522	2.0-0.0014	17	0.378	2.0-0.04	8	0.372	3.0-0.03	27
P	3.78	6.83-1.49	3	19.9	32.2-11.07	8	12.75	25.13-1.18	15
K				4.21	7.16-2.49	6	2.76	6.15-0.83	13
Si				39.5	39.5	1	162.0	334.0-73.0	3
Ag	0.243	1.0-0.08	11	0.150	0.22-0.1	3	0.195	0.50-0.08	4
Na	3.96	10.-0.5	8	4.44	7.88-1.0	2	6.15	10.0-2.0	5
Sr	0.13	0.14-0.12	3	0.155	0.21-10.0	2	0.26	0.26	1
S				10.1	11.6-7.6	6	12.3	32.5-1.64	14

TABLE 14 Cont'd.

Summary of Major and Minor Elements in Sludge

(Milligram per Gram Dried Sludge)(34)

Elemental Analysis	Primary Sludge			Activated Sludge			Digested Sludge		
	Average	Range	No. in Sample	Average	Range	No. in Sample	Average	Range	No. in Sample
Sn	0.95	2.0-0.5	8	0.5	0.5	1	0.60	0.70-0.50	3
Ti	14.8	20.0-5.0	8	11.8	20.0-0.50	3	14.2	20.0-1.0	3
V	2.09	15.0-0.3	11	0.70	0.89-0.51	3	5.20	10.0-0.32	4
Zn	6.87	25.0-0.34	18	3.29	6.3-0.13	13	4.04	11.0-0.5	39
Zr	1.72	10.9-0.3	8	10.0	10.0	1	2.03	5.0-0.10	3
Ca	0.063	0.1-0.01	7	0.05	0.05	1	0.05	0.05-0.05	3

Wastewater sludges contain many fertilizing elements. In comparison with commercial fertilizers, they are rated principally on their content of three substances: nitrogen as N, phosphorus as P or as phosphoric acid (P_2O_5), and potassium as K or potash (K_2O). The concentration of these three elements is expressed as a percentage of the dry weight of the solids. Compositional data obtained from various literature sources are compiled in Table 15. It appears that the fertilizing ingredients of the sludge depend on the type of processes used in the wastewater treatment plant. In general, N ranges from 0. 8 to 5% for plain sedimentation solids, and 3. 0 to 10% for activated sludges. Nitrogen content in trickling filter humus depends on the length of its storage in the filter and it will vary from 1. 5 to 5%. Anaerobic digestion drastically reduces the nitrogen content of the sludge (40 to 50%). The phosphate content of the sludge is rather small ranging from 1 to 4%, and the potash content is even smaller ranging from 0. 1 to 0. 5% (10).

For a better understanding of the sludge fertilizing potential, the fertilizing ingredients of wastewater sludge compared with various manures and organic nitrogen material are presented in Table 16. Minor elements present in sludge are also often important in crop nutrition. A list of these elements for activated and digested sludge is presented in Table 17.

A comparison of various types of sludge based on their humus content was made by Hasmann (39). Results of his study are tabulated as follows:

Sludge Type	Humus Content %
Fresh	33
Digested	35
Activated	41
Trickling Filter	47

CHARACTERISTICS OF WATER TREATMENT PLANT SLUDGE

Characteristics of the sludge from water treatment plants are highly variable depending on such factors as : sources of raw water; type of treatment process employed; types of chemicals added; efficiency of unit operation: degree of solids removed; and the time between basin and filter backwash clean-out.

The sources and hence, the quality of the raw water will have a significant effect on the physical, chemical, biological, and quantitative characteristics of the sludge produced. Sources of raw

TABLE 15
Chemical Composition of Sewage Sludges
(Dry Weight Basis)

Sewage Treatment Plant	Nitrogen (%)	Carbon (%)	Carbon-Nitrogen Ratio	Phosphoric Oxide (%)	Ash (%)	pH	Ref. No.
Washington, D.C.[1]							
Influent solids (spring)	2.42	43.46	18.0	1.14	32.35	5.3	35
Influent solids (summer)	2.39	43.69	18.3	1.09	37.59	5.6	35
Digested sludge	2.06	28.59	13.9	1.44	52.83	5.8	35
Baltimore, Md.							
Influent Solids	2.23	47.09	21.1	1.29	24.16	5.7	35
Activated sludge	2.36	30.37	12.9	11.01	29.70	5.5	35
Humus tank sludge	5.34	37.90	7.1	3.96	32.30	5.9	35
Heat-dried dig. sl.	3.05	36.53	12.0	2.97	39.73	5.0	35
Jasper, Ind.[2]							
Influent solids	2.90	42.31	14.6	1.62	32.29	5.7	35
Activated sludge	3.51	23.01	6.6	2.81	52.43	6.8	35
Digested sludge	5.89	22.95	3.9	3.49	36.96	5.8	35
Richmond, Ind.[3]							
Influent solids	3.80	28.21	7.4	5.19	40.94	7.6	35
Activated sludge	3.02	44.04	14.6	3.64	31.37	6.2	35
Digested sludge	2.24	26.36	11.8	4.34	50.09	6.9	35
Chicago, Ill. (Southwest plant)[4]							
Raw sludge	2.70	46.62	17.3	2.71	28.24	4.5	35
Activated sludge	4.98	28.62	5.7	5.58	34.82	6.2	35
Heat-dried sludge	5.56	29.41	5.3	6.56	37.42	6.0	35
Milwaukee, Wis.[4]							
Heat-dried sludge	5.96	20.88	3.5	3.96	27.73	4.8	35
Rochester, N. Y.							
Digested sludge	2.54	--	--	1.16	42.80	--	12
Des Moines, Ia.							
Digested Prim. & Act. Sludge	1.81	--	--	3.31	61.40	--	12
Phoenix, Ariz.	1.07	12.90	12.1	0.78	74.80	--	36
Chandler, Ariz.	2.48	43.30	17.5	--	31.70	--	37

[1] Primary treatment.

[2] Prevalence of home garbage grinders affects sludge composition.

[3] Ground garbage discharged directly to digesters.

[4] Sludge not digested.

TABLE 16

Fertilizing Ingredients in Sewage Sludges, Various Manures and Organic Nitrogenous Materials

Material	Fertilizing Ingredients (%)			
	Nitrogen (N)	Phosphoric Acid	Potash	Organic Matter
Digested settled sludge	0. 8-3. 5	0. 7-4. 0^{2}	------	------
Digested settled sludge with trickling filter sludge	1. 0-4. 5	tr. -4. 0^{2}	0. 8-1. 6^{3}	30-60^{3,4}
Digested activated sludge	2. 0-4. 5	1. 0-3. 6^{2}	------	------
Heat dired-activated sludge	4. 0-7. 0	1. 7-2. 5	0. 13	------
Commercial pulverized				
Sheep manure	1. 2-2. 5	1. 0-2. 0	2. 0-4. 0	48
Cattle manure	1. 6-2. 1	1. 0	1. 0-2. 2	66
Poultry manure	1. 9-4. 0	2. 5-3. 7	0. 8-1. 3	64
Animal tankage	5-10	7-16	-------	------
Blood	9-13	0. 5-14	-------	------
Fish scrap	6. 5-10	5-10	-------	------
Cottonseed meal	5-8	2-3	1-2	------
Castor pomace	5-6	2	1	------

---

[1] See Reference 1

[2] Dry basis

[3] Estimated from other tablets

[4] Volatile matter

TABLE 17

Minor Chemical Elements in Activated Sludge and Digested Sludge[(38)]

	Element (ppm)				
Sludge	Copper	Zinc	Boron	Manganese	Molybdenum
Activated sludge:					
Min	385	950	6	65	6
Max	1, 500	3, 650	74	190	45
Avg.	916	2, 500	33	134	16
Digested sludge:					
Min	315	1, 350	4	30	2
Max	1, 980	3, 700	15	790	12
Avg.	643	2, 459	9	262	6

water can be influenced by many factors, such as seasonal variations; changes in the utilization of a watershed area; the nature of the discharge from municipalities and industries at the upstream portion of the source; and the degree of ground water contamination.

Some of the more significant reasons for knowing the characteristics of the water treatment plant sludge include: (1) to provide a means for assessing the pollution hazards to the immediate environment of the receiving water; (2) to establish a basis for advancing the technology for facility design in conditioning, thickening, dewatering, and disposing of the sludge; and (3) to allow for recovery of chemicals and effective utilization of the sludge by-products.

The literature reveals that not much effort has been made to characterize these sludges in the past as compared with wastewater and industrial sludges. However, more recently the AWWA Research Foundation, EPA, and State agencies for New York and Ohio have increased their efforts in this area. Standard methods were not found for sampling and analyzing the physical, chemical, and biological composition of these sludges. The information that appears in the literature is rather fragmentary and inconsistent. Therefore, it is necessary to first, outline the parameters that define the characteristics of these sludges and then collect and organize the reported information pertaining to the characteristics of sludges produced from the various types of treatment processes.

The significant parameters for characterizing sludges from water treatment plants are: (1) solids, (2) settleability, (3) filterability, (4) viscosity, and (5) to a lesser extent, coliform content, BOD, COD, TOC, and pH, and chemical composition.

Solids content of the sludge is important to the extent that it adversely affects the immediate environment of the receiving waters by increasing water turbidity, dissolved solids, discoloring of water, formation of sludge blankets, and possible toxicity. These solids can be acidic, alkaline, or neutral. Solids containing biodegradable organic material will exert an oxygen demand (43).

Settleability of the sludge is another important factor which is influenced by many variables, such as: viscosity of the liquid; solids content; size and configuration of the settling basins; and the physical, chemical, and electrostatic nature of the suspended material.

Viscosity of the sludge is needed to predict the friction head loss of the sludge transported by pipelines. It has been reported (48) that sludge with solids content above 1% exhibits non-Newtonian flow characteristics and, therefore, the viscosity of the sludge is referred to as "apparent viscosity".

Coliform content of the sludge depends on the source and quality of the raw water used. Sludge with a high concentration of pathogenic bacteria could be extremely detrimental to the quality of the receiving water. For determining the pathogenic bacteria of the sludge, E. coli concentration is normally used as an indicator.

Inorganic constituents of the sludge from water treatment plants are important parameters which reflect the chemical nature of the sludge. Knowledge of these constituents is useful. when recovery of chemicals or utilization of the sludge is to be considered. The level and concentration of the chemical content depend upon the source of raw water and the type of chemicals employed in the treatment processes.

Water treatment plant sludge characteristics vary significantly depending upon the parameters mentioned above. Sludge characterization can be studied thoroughly if sludge from various treatment processes are considered separately.

Purification or Coagulation Sludge

The two major types of sludge resulting from a municipal water purification plant are: (1) basin sludge; and (2) filter backwash sludge. Basin sludge is highly complex in nature. It is comprised of the organic, inorganic, and biological organisms present in raw water in a state of solution, colloidal suspension or readily settleable form; or it may be mixed with the coagulant or coagulant aids employed in the treatment process. The sludge is described as a fluffy agglomeration of chemical precipitates and organic debris, and is high in moisture content (98-99%) (43). The agglomeration is difficult to dewater, but is readily settleable. The color of the sludge approaches yellow-orange, pale-green, dark-brown, and sometimes black; depending on the type of chemical processing used, the nature of impurities extracted, and the stage of the organic material.

A series of tables and figures have been assembled to describe the general characteristics reported for basin sludge. Table 18 is an outline of the principal constituents of basin sludge; Table 19 presents data on solids, BOD, COD and pH of basin sludge as reported by Russelman(43). Table 20 is a compilation of the same

TABLE 19
Coagulation Sludge Characteristics[43]

Plant	Treatment	Plant Capac. mgd	BOD (5-day) mg/l	COD mg/l	pH	Total Solids mg/l	Volatile Solids mg/l	Total Suspended Solids mg/l	Volatile Suspended Solids mg/l
A	Alum Coagulation & Sedimentation	25	41 72 (1) 144 (2)	540	7.1	1,159	571	1,110	620
B	Alum Coagulation, Clarifier	2	90	2,100	7.1	10,016	3,656	5,105	2,285
C(3)	Alum Coagulation, Clarifier	1	108	15,500	6.0	16,830	10,166	19,044	10,722
D	Alum Coagulation, Clarifier	10	44	---	6.0	---	---	15,790	4,130

(1) BOD after 7 days
(2) BOD after 27 days
(3) Activate carbon in sample

TABLE 20
Characteristics of Basin Sludge

Plant Location	T. S. mg/l x 10^3	S. S. mg/l x 10^3	V. S. mg/l x 10^3	BOD mg/l	COD mg/l	pH	Reference #
Shermount Plant Rochester, N. Y.	4. 35	3. 61	1. 50	33-77	500-1000	7	44, 47
Wolcott Plant Wolcott N. Y.	4. 26	3. 58	1. 02	45	1048	7	44, 47
Ithaca, N. Y.	6. 32-19. 48	6. 19-18. 84	24. 04-34. 51*	5-3	-----	7	48, 47
Blacksburg-Christamburg, V. P. I. Water Authority	17. 35	----	4. 12	380	1320	6. 6	42
Howard Ave. Plant Milwaukee, Wisc.	8. 050	7. 75	3. 32	----	----	7. 0	50
Piqua Municipal Plant Piqua, Ohio	23-31	95-97*	26-28*	14-21	320-350	10. 4	

*% of T. S.

sludge characteristics as reported for several different plants. Table 21 shows the changes of viscosity as the solids content changes, and Table 22 is a tabulation of the chemical composition of basin sludge. Reported (48) values of specific resistance range from 0.1×10^{10} to 0.44×10^{10} sec^2/gr. Lime is often used for coagulation purposes and this greatly improves the sludge handling characteristics. However, sludge filters more like a tertiary sludge and generally much poorer than a raw primary sludge. Studies on the settleability of the sludge showed that basin sludge exhibits zone settling characteristics (48, 49). The bacterial content of the basin sludge ranges from 2 to 190% of comparable concentrations in the river water supply, as reported by Sutherland (44). Dean (45) has reported that the coliform content of the basin sludge varies from 0 to 42% as E. coli concentration of the river water supply.

TABLE 18: Principal Constituents of Purification Wastes

Alum Coagulation*	Iron Salt Coagulation*	Lime and Iron Salts Coagulation
Al $(OH)_3$	Fe $(OH)_3$	$CaCO_3$
Inorganic Solids	Inorganic Solids	Inorganic Solids
Organic Solids	Organic Solids	Organic Solids
Activated Carbon	Activated Carbon	Activated Carbon
Coagulant Aids	Coagulant Aids	Coagulant Aids

*Reference 43

Characteristics of the filter backwash waste are essentially the same as the basin sludge, but in far less concentration. This sludge contains fine clay particles, hydroxides of aluminum and iron, activated carbon, oxides of iron, debris, chemicals precipitated from the filter media, and small portions of the media itself. Typical values for the various characteristics of the sludge are shown in Tables 23 to 25.

Softening Sludges

In municipal water softening plants, the hardness producing minerals are removed either by a conventional softening process which utilizes chemical precipitation using lime, lime-soda, or lime caustic; or, by an ion-exchange softener.

Conventional or chemical precipitation sludge is more predictable than coagulation sludges. The principal constituents are

TABLE 22
Chemical Analysis of Basin Sludge

Location & Ref. No.	T.S. %	$CaCO_3$ %	$Mg(OH)_2$ %	$Al(OH)_3$ %	Fe_2O_3 %	SiO_2 %	Volatile Matter %	Remainder
Centralia(53)	0.5	41.9	13.3	8.7	6.4	6.4	--	23.3
Olney(53)	0.9	41.3	20.1	4.4	4.6	3.4	--	26.2

TABLE 23

Filter Backwash Characteristics (43)

PLANT	Treatment	BOD (5- day) mg/l	COD mg/l	pH	Total Solids mg/l	Volatile Solids mg/l	Total Suspended Solids mg/l	Volatile Suspended Solids mg/l
A	Alum Coagulation & Sedimentation	4. 2	28	7. 8	121	44	47	31
B	Alum Coagulation & Clarifier	3. 7	75	7. 2	378	115	104	53
C	Alum Coagulation & Clarifier	2. 8	160	7. 8	166	45	75	40
D	Alum Coagulation & Clarifier	1. 8	---	---	---	---	100	60
E	Lime-ferric Coagulation & Sedimentation	3. 2-4. 1	18-27	9. 9	731-864	216-285	695-825	---

TABLE 24
Suspended Solids in Filter Backwash(53)

	Pounds/sq. ft.**		Concentration, mg/l	
Municipality	Range	Average	Maximum	Avg. Max.
Centralia, Ill.	0. 11-0. 16	0. 14	1, 167	920
Evanston, Ill.	0. 0800. 20	0. 14	958	766
Olney, Ill.	0. 23-1. 10	0. 58	5, 212	2, 932
Streator, Ill.	0. 04-0. 15	0. 10	1, 053	687
Dayton, Ohio	----------	----	2, 350	1, 650
Sidney, Ohio	----------	----	1, 120	874

**Filter

TABLE 25
Chemical Analysis of Filter Washwater(52)

		Purification	Softening
Volatile Matter	Range	0.5-40	4.5-99.06[e]
	Samples	15	3
SiO_2	Range	0.65-69[a]	0.1-18.8
	Samples	15	7
Fe_2O_3	Range	0.08-18.4	0.06-20.1
	Samples	11	7
Al_2O_3	Range	0 -45[b]	0-34.1
	Samples	13	6
$CaCO_3$	Range	1-55.8[c]	0.35 -98[f]
	Samples	12	7
$Mg(OH)_2$	Range	0.3-22.1	0.1-6
	Samples	10	6
Remainder	Range	2-70.3[d]	0.53-54.41
	Samples	10	6

a - Rochester, N. Y.
b - Detroit, Michigan
c - San Diego, California
d - Pittsburgh, Pennsylvania
e - Bismarck, North Dakota
f - Bismarck, North Dakota

$Mg(OH)_2$, $CaCO_3$, turbid matter, suspended solids, and coagulant aids. The volume of the sludge produced is greater than that of coagulation sludges. Reportedly, up to 3.5 lbs. of dry solids are produced per pound of hardness removed when lime-soda are the principal coagulants (54, 55), and up to 1.7 lbs. when lime-caustic are the principal coagulants (55). Sludge color ranges from pure white to pale-yellow. Solids content of the sludge reportedly ranges from 2 to 33% (54). The physical characteristics of the sludge are such that it remains a fluid up to about 15% solids content. The sludge is thixotropic between a solids content of 25 to 70%. For solids content above 70%, the sludge appears compactible and loses its thickness (55). Chemical compositions of these sludges are presented in Table 26. The specific resistivity of the sludge ranged from 0.13×10^8 to 4.2×10^8 sec^2/gr for sludges containing 1.5 and 14.5% solids, respectively.

TABLE 21
Apparent Viscosity of Settling Basin Sludge
(Measured at a Shear Rate of 2000) (48, 51)

Percent Solids by Weight	Apparent Viscosity at 20°C- g/cm-sec.
Distilled Water	0.010
1.2	0.0347
1.88	0.0458
2.58	0.0583
3.27	0.117

Characteristics of the ion-exchange brine wastes produced as the results of regeneration are given in Table 27. Volume of the waste has been reported to range from 3 to 10% of the volume of water treated. The chloride content is very high, ranging from 9000 to 25,000 mg/l. Additional information regarding the characteristics of the sludge was not available in the literature.

Diatomite Earth Waste Characteristics

Characteristics of the sludge are almost the same as that of diatomite earth itself. The reason is that the amount of filter aid used is usually twice that of the impurities extracted from the raw water. It has a dry density of about 10#/cu ft., and specific gravity of about 2.0 (57). Russelmann (43) has reported BOD values of 105 mg/l, COD of 340 mg/l, pH of 7.6 and total solids content reaching over 7000 mg/l. Other information found in the literature pertaining to the characteristics of these sludges is presented in Table 28.

TABLE 26

Dry Solids Content of Basin Sludge Mean Values(53)

	Municipality	T.S. %	$CaCO_3$ %	$Mg(OH)_2$ %	$Al(OH)_3$ %	Fe_2O_3 %	SiO_2 %	* %
	(surf. - soft)							
1.	Bloomington	2.3	85.2	9.5	3.7	0.3	0.6	0.7
2.	Canton	1.9	67.3	9.0	1.3	0.7	0.9	21.8
3.	Decatur	2.8	80.0	11.7	2.0	2.7	1.7	1.9
4.	Eureka	2.3	66.1	18.7	2.2	0.5	0.7	13.8
	(well - soft)							
5.	Champaign (E)	20.0	79.6	6.3	0.4	2.2	2.0	9.5
6.	Elgin (Slade)	32.2	86.0	4.3	0.3	0.9	0.2	8.3
7.	Normal	22.2	82.4	11.8	0.3	1.5	0.7	3.3

TABLE 27

Analysis of Waste Brines from Ion-Exchange Softener

Constituent	Amount mg/l Reference #56	Amount mg/l Reference #54
Calcium	1,720	3,000 - 6,000
Magnesium	600	1,000 - 2,000
Sodium	3,323*	2,000 - 5,000
Sulfate	328	------
Chloride	9,600	9,000 - 22,000
Total Dissolved Solids	15,656	-------
Total Hardness	7,762	-------

*includes potassium also

TABLE 28

Characteristics of Diatomite Earth Filter Waste

Process Wastes Item	Diatomite Filtration	Conventional Filtration	
Origin of Wastes	Filter Backwash	Sedimentation Basin Sludge	Filter Backwash
Typical Magnitude of Wastes			
Volume, percent of throughput, range;	0.1 - 0.5	0.05 - 0.1	0.5 - 3
Suspended solids, concentration, range, mg/l;	10,000 - 15,000	5,000 - 50,000	150 - 400
Suspended solids, weight, lbs/million gals throughput.	100 - 400	100 - 250	10 - 50
Typical Characteristics			
Settleability	Filter aid- good Entrapped turbidity-varies from poor to good	Good	Fair
Putrescibility	Negligible or minor	Varies with nature of solids removed and whether or not sludge removal is continuous or intermittent	Negligible
Abrasiveness	Pronounced	Usually None	None
Porosity	Pronounced	Usually None	None
Drainability	Good	None	Poor to fair
Form of Solids	**Rigid**	**Amorphous**	**Amorphous**

SLUDGE HANDLING AND TREATMENT

The aim and ultimate goal for application of physical, biological and chemical processes in a wastewater treatment plant is to remove and concentrate that portion of the wastewater that is responsible for the offensive nature of the waste flow. Thereby, the major part of the flow is allowed to return to the environment. The concentrated pollutants are called sludge. They are generally in suspended solids form with little tendency for consolidation. Most sludges are biologically unstable substances. They provide food for microorganisms which grow in and upon them, resulting in a stable material, and obnoxious and odorous byproducts. The enormous quantities of microorganisms associated with sludge are a definite hazard to human health. These microorganisms are mostly of fecal origin and many of them are pathogenic. Therefore, sludge stabilization and treatment seem an obvious necessity. Sludge treatment often includes stabilization (making the sludge biologically inert and reducing its content of pathogens by many orders of magnitude), volume reduction, and solid-liquid separation. A flow diagram of the most common methods used for sludge processing and disposal is shown in Figure 8.

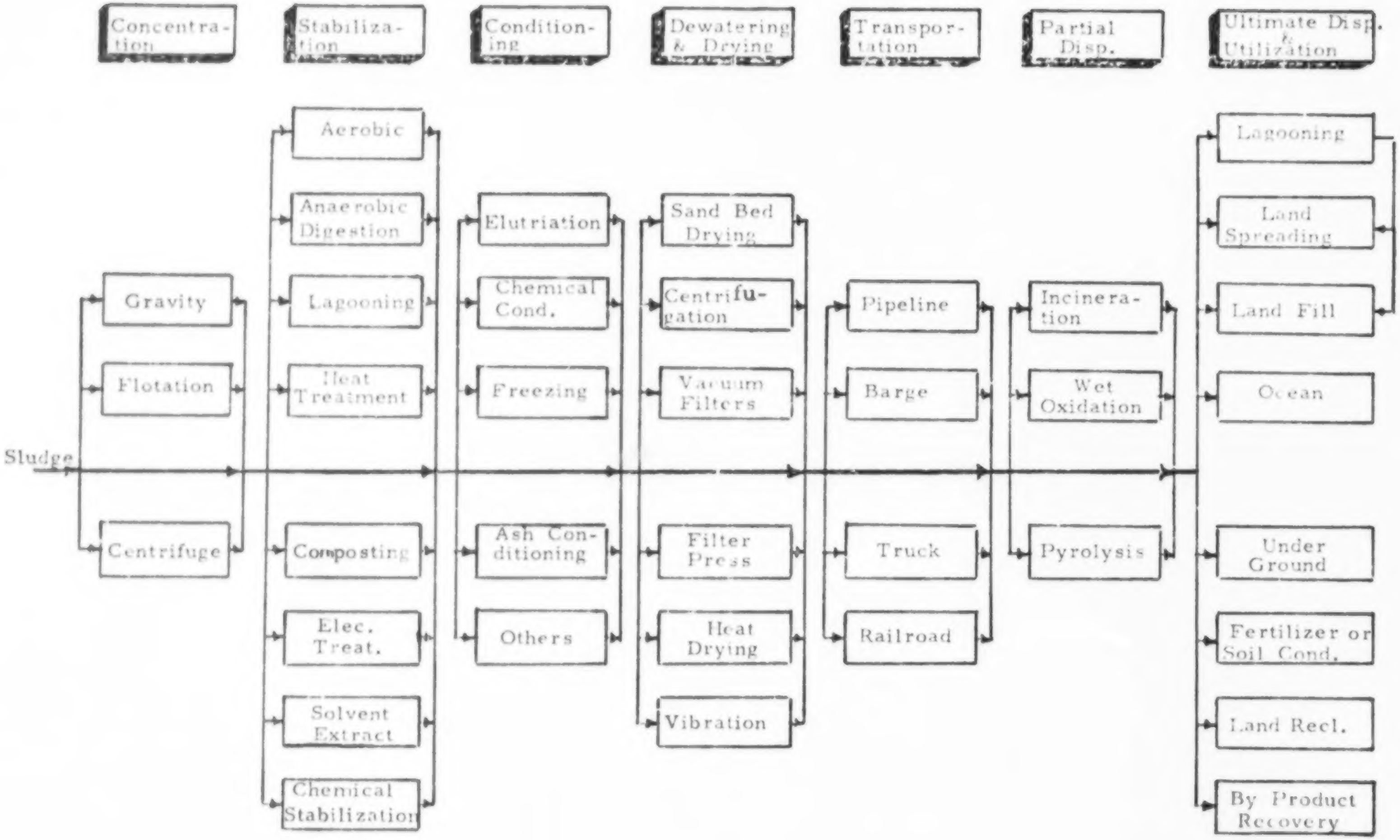
SLUDGE CONCENTRATION

Concentration is applied to increase the solids content of the sludge, thus reducing its volume significantly. Sludge concentration might be desirable when: (1) pipeline transportation of the sludge is involved, (2) liquid sludge is applied on farm land, and (3) savings of chemicals, heat energy, and auxiliary fuel in the subsequent steps are questions of concern.

Where sludge is disposed of by dumping into the sea, as is being practiced in many coastal cities, sludge concentration could result in significant cost reduction by reducing pipe size and pumping equipment and barge sizes and trips. Sludge concentration also results in reduction of the amount of chemicals used for conditioning and dewatering of the sludge; reducing the digester capacity requirements and digester heat requirements; and the amount of auxiliary fuel required for heat drying and/or incineration etc. (17)

Methods used for sludge concentration or thickening include: (1) gravity thickening, (2) dissolved air flotation, and (3) centrifugation.

Figure 8
Unit Processes for Sludge Handling, Treatment, and Ultimate Disposal


Concentration
Stabilization
Conditioning
Dewatering & Drying
Transportation
Partial Disp.
Ultimate Disp. & Utilization
Sludge
Gravity
Flotation
Centrifuge
Aerobic
Anaerobic Digestion
Lagooning
Heat Treatment
Composting
Elec. Treat.
Solvent Extract
Chemical Stabilization
Elutriation
Chemical Cond.
Freezing
Ash Conditioning
Others
Sand Bed Drying
Centrifugation
Vacuum Filters
Filter Press
Heat Drying
Vibration
Pipeline
Barge
Truck
Railroad
Incineration
Wet Oxidation
Pyrolysis
Lagooning
Land Spreading
Land Fill
Ocean
Under Ground
Fertilizer or Soil Cond.
Land Recl.
By Product Recovery

Gravity Thickening

Gravity thickening is the most simple, inexpensive, and widely used sludge concentration method in wastewater treatment plants. This process is basically the same as sedimentation settling, but relatively slow in action.

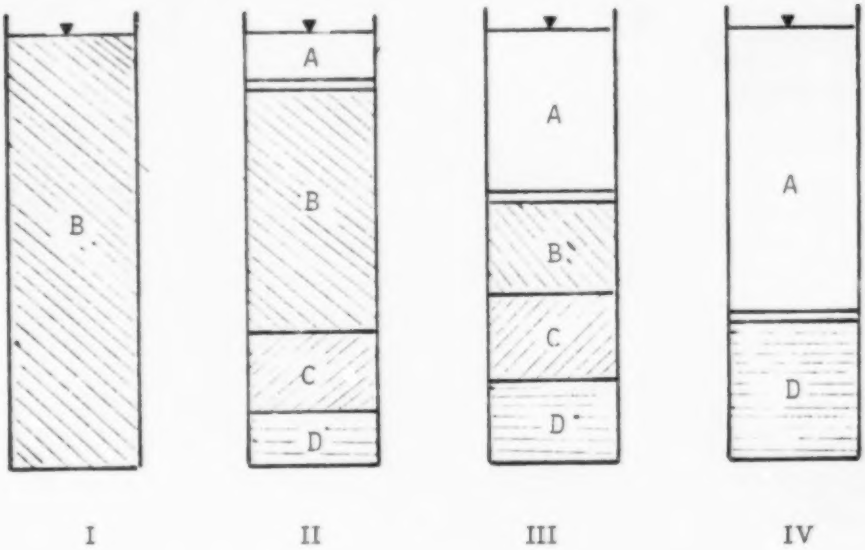
According to Burd (17) gravity thickening usually exhibits the "hindered" settling phenomenon. Hindered settling is influenced by such factors as particle size distribution, density, concentration and agglomeration of the particles, as well as hydraulic conditions in the settling basin (65). In a gravity thickening process, different zones have been distinguished, as shown in Figure 9. These zones include: (A) clarification zone or zone of clear supernatant liquid, (B) settling zone characterized by a constant rate of solids settling, (C) compression zone characterized by a reduction in the rate of solids settling, and (D) compaction zone or zone of minimal settling rate. Several investigators (16, 67) have reported that data obtained from a batch settling test can be used safely as a basis for design of a continuous thickening unit. Settling curves can be utilized to determine the surface area required for clarification and the surface area required to thicken the sludge to a particular solids concentration. Plotting and utilization of settling curves for design purposes have been discussed previously. A comprehensive investigation of the relationship between settling properties of continuous thickening has been reported by Dick (68).

Solids concentration obtained using mechanical thickeners varies considerably, depending on factors such as sludge types and characteristics; initial concentration of the sludge; particle size distribution, shape and density; sludge age and temperature; and the ratio of organic to inorganic content of the sludge. Sludge thickening using separate handling units has been found to produce a greater concentration of solids than by thickening in the initial wastewater clarification unit (17).

Degree of sludge concentration obtained and the efficiency of thickener operation depend on the following factors. Initial solids concentration and temperature of the sludge in the thickener is important. As shown in Figure 10, an increase in initial solids content reduces the efficiency of thickener drastically, where an increase in temperature to a certain degree enhances degree of concentration obtained. Also, the type of sludge and its volatile content effect sludge concentration in a manner shown in Figure 11 (70). The reason for lower degree of concentration of the combined primary and biofilter

Figure 9

Thickening Zones(66)



A- represents clarification zone

B- represents settling zone

C- represents compression zone

D- represents compaction zone

Figure 10

Effect of Temperature and Initial Concentration on the % Increase in Fresh Solids Concentration (after 96 hours)[69]

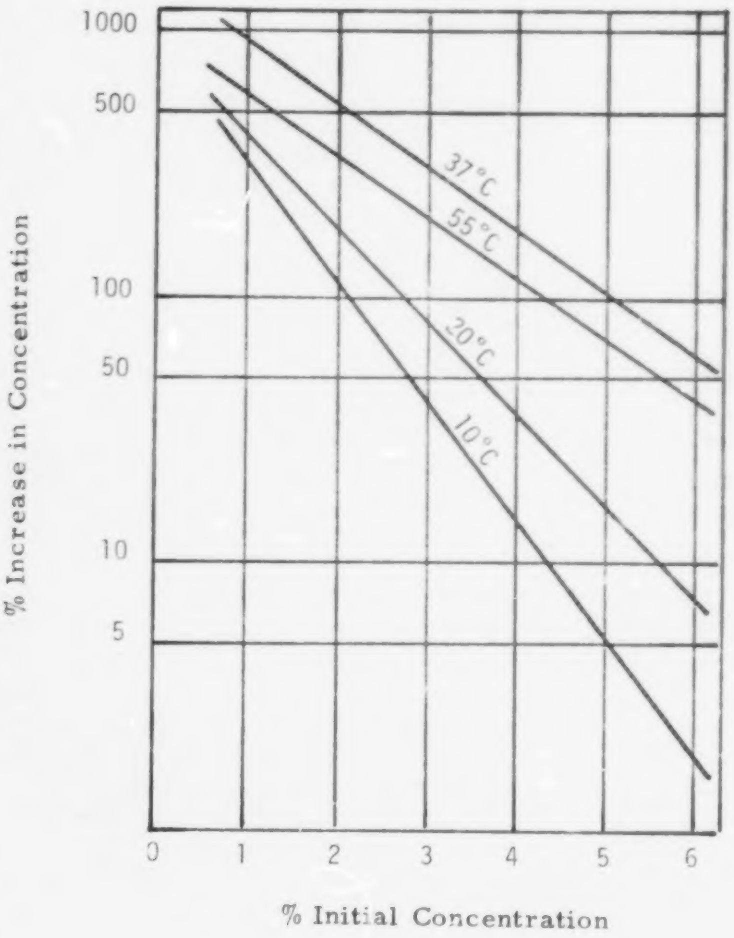
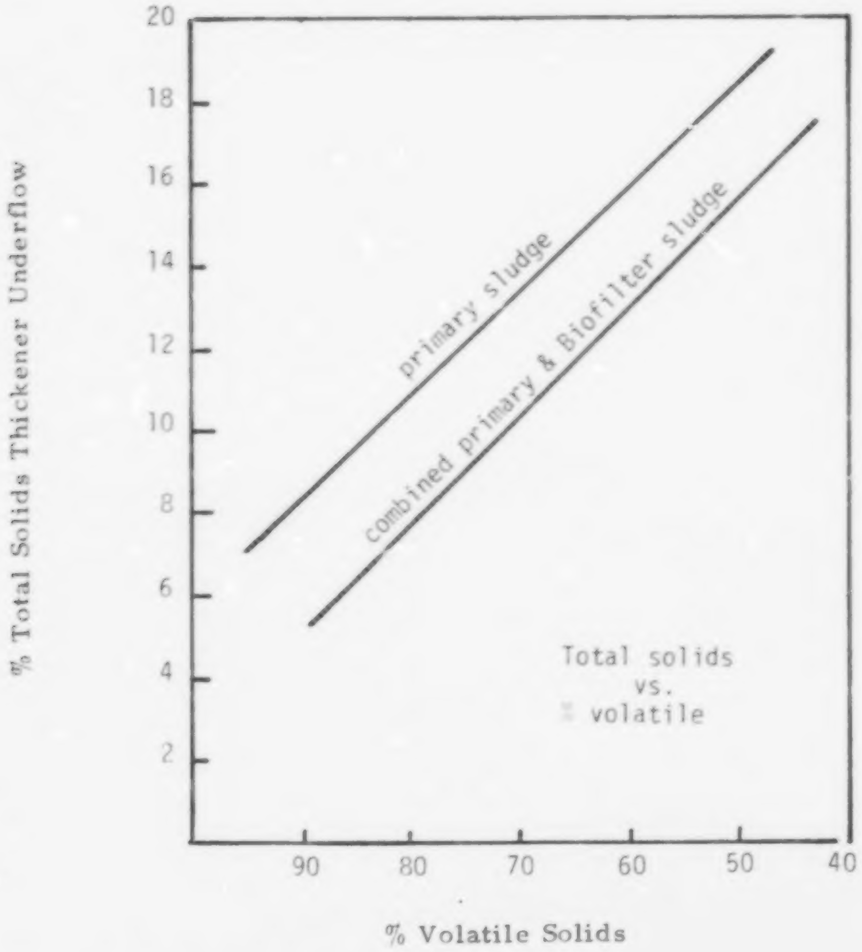


Figure 11

Relationship of Total Solids to Percent Volatile Solids(70)



sludge is due to the presence of biological sludge. It is believed that biological sludges, particularly activated sludge, are generally bulky in nature and have shown a relatively lower degree of concentration as compared with non-biological sludges. Concentration is influenced by the addition of chemicals and inert weighing agents. Rudolfs (71) has observed that alum and ferric salts did not change the concentration significantly and sulfuric acid, iron oxides, diatomaceous earth, and fly ash were insignificant at reasonable dosage rates. Lime dosages of 250 to 500 ppm, on the other hand, increased sludge concentration significantly. Successful use of polyelectrolytes as an aid to sludge compaction, increase in settling rates and overhead clarity have also been reported in the literature.

Dust (72) has reported that under normal operations thickening produced about 8.7% solids concentration for combinations of primary and trickling filter sludge. Keefer (73) has reported that raw primary, waste activated and trickling filter sludge was concentrated to as much as 8.5% solids content. Voshel (74) has reported that sludge concentration of up to 7% solids content was obtained using picket-type thickener for activated sludge. Typical concentration that can be obtained for various types of sludges by applying mechanical thickeners are presented in Table 29 (14).

TABLE 29
Concentrations of Unthickened and Thickened Sludges and Solids Loadings for Mechanical Thickeners(14)

Type of sludge	Sludge, percent solids		Solids loading for mechanical thickeners, lb/sq ft/day
	Unthickened	Thickened	
Separate sludges:			
Primary	2.5-5.5	8-10	20-30
Trickling filter	4-7	7-9	8-10
Modified aeration	2-4	4.3-7.9	7-18
Activated	0.5-1.2	2.5-3.3	4-8
Combined sludges:			
Primary and trickling filter	3-6	7-9	12-20
Primary and modified aeration	3-4	8.3-11.6	12-20
Primary and activated	2.6-4.8	4.6-9.0	8-16

Flotation Thickening

The literature shows that flotation thickening of wastewater sludges is becoming increasingly popular over gravity thickeners. The basic principle in flotation thickening is to attach the minute air bubbles to the suspended solids of the sludge. This reduces the specific gravity of the solid particles below that of water and causes the solids to separate from the liquid phase while moving in an upward direction. According to Rich (66), entrapment of rising air bubbles in the floc particles is the predominant action with flocculant materials such as activated sludge, and in the case of non-flocculant particles, contact of air bubbles and particles by adhesion has more significance, which depends highly on the surface properties of the solid particles.

Flotation thickeners have been widely used in wastewater treatment plants, primarily in conjunction with waste activated sludge. Thickened sludge having solids content of 4% with 85% solids recovery without use of chemicals has been reported (14). Where a mixture of primary and activated sludge was used, solids concentration averaging 6% and reaching as high as 8% was obtained (14). Table 30 shows average sludge concentration obtained without use of chemical aids.

TABLE 30
Sludge Solids Produced by Flotation Thickener(75)

Combined primary and activated sludge	6.1%	Solids
Combined primary and activated sludge	7.4%	"
Activated sludge only	4.9%	"
Activated sludge only*	3.7%	"
Primary + activated sludge 1:1		
Cannery waste in season	5.3%	"
Cannery waste our of season	7.1%	"

*Same as above, but higher volatile content

Use of chemical aids has resulted in an increase in solids concentration, as well as percent solids recovery. Dick (68) has reported from the results of other studies that for plants not using polymers, float solids content averaged about 4% with solids recovery of about 90%. For plants using polymers, float solids contents were up to 5.8% with solids recovery of 98.6%. Table 31 shows results of a survey of various treatment plants applying air-flotation thickening for activated sludge by Bernard and Eckenfelder (76).

TABLE 31

Flotation Thickening Units$^{(76)}$

Installation	Type Sludge	Feed Solids Conc. (%)	Thickened Sludge (%)	Solids Recovery (%)	Loading (psfd)	Chemical Aids
Bernardsville, N.J.	A	1.70	4.3	98.8	103.0	+
Hatboro, Penna.	A	0.73	4.0	96.0	69.5	+
Omaha, Neb.	A	2.00	5.9	99.8	183.0	+
Belleville, Ill.	A	1.83	5.7	98.7	91.0	+
Indianapolis, Ind.	A	0.30	5.0	95.0	50.5	+
Warren, Mich.	A	0.60	7.0	95.0	125.0	+
Frankenmuth, Mich.	A	0.90	7.0	99.1	156.0	+
Oakmont, Penna.	A	0.63	8.0	98.7	72.0	+
Columbus, Ohio	A	0.68	5.0	99.5	79.0	+
Levittown, Penna.	A	0.57	5.5	99.4	70.0	+
Nassau Co., N.Y.	A	0.81	4.4	99.6	118.0	+
Nashville, Tenn.	A	1.54	12.4	99.6	123.0	+
Fort Worth, Texas	A	0.90	4.5	99.8	108.0	+
Toledo, Ohio	A	0.82	7.3	99.6	89.0	+
Cleveland, Ohio	A	0.45	4.5	99.3	77.0	+

A = waste-activated sludge

Burd (17) has discussed four methods of flotation thickening used in wastewater sludges. The basic principle which is common in all of the four methods is that of rising of gas bubbles to increase the buoyancy of the solid particles. These methods included: (1) dispersion-air flotation where bubbles are generated by introducing air through a revolving impeller or porous media; (2) dissolved-air pressure flotation, where air is put in solution under elevated pressure and later released under atmospheric pressure; (3) dissolved-air vacuum flotation, which applies a vacuum to wastewater aerated at atmospheric pressure; and (4) biological flotation, where the gases formed by natural biological activities are utilized to float solids. Among the above four methods dissolved-air flotation and biological flotation have received wide use in sludge handling because of higher solids concentration obtained. Dispersed-air and dissolved-air vacuum flotation are generally applied for wastewater clarification purposes.

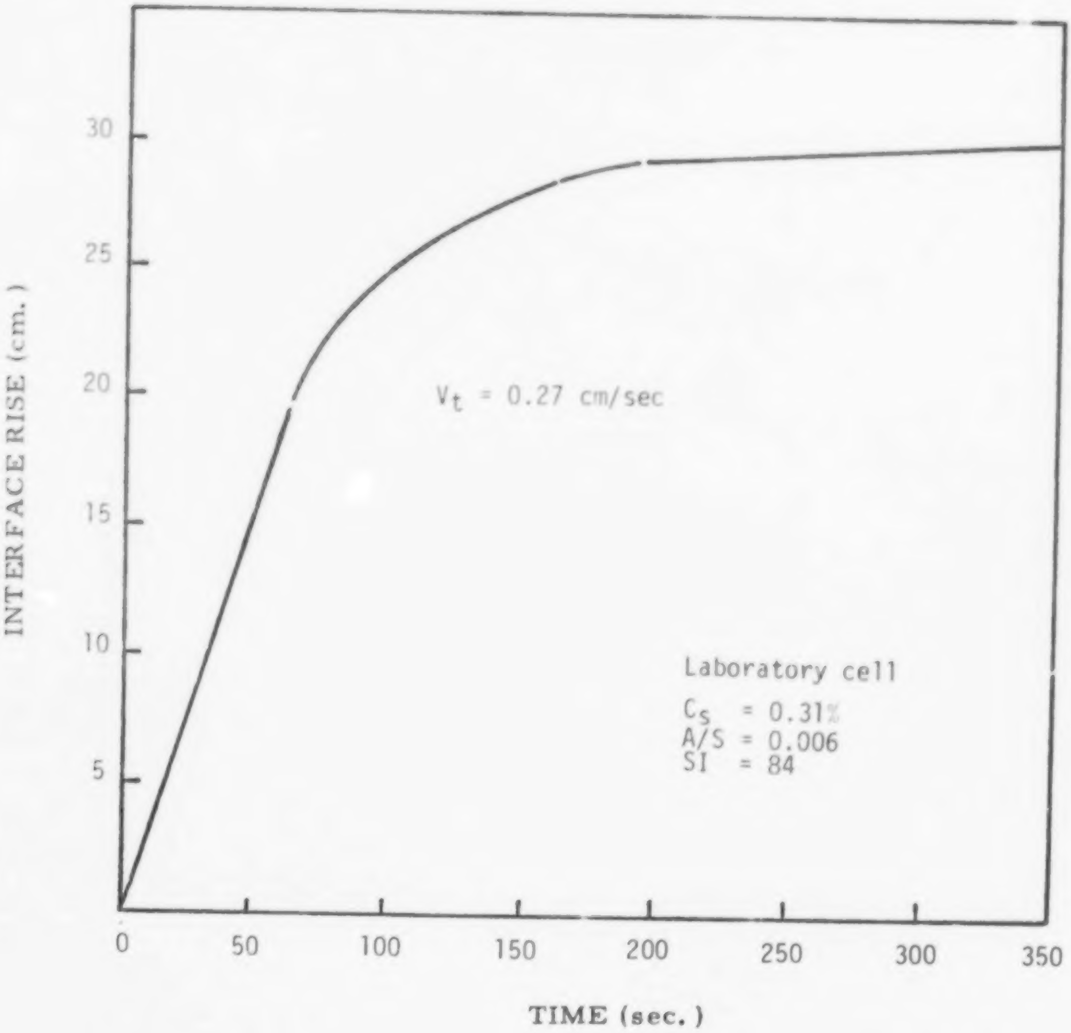
Mechanism of solids thickening by flotation thickening is analogous to that of gravity sedimentation. Therefore, it is referred to as "hindered" separation or flotation. A typical flotation curve is shown in Figure 12. The degree of sludge thickening depends on factors such as compressional force and the surface active properties of the solids resisting compression (78). The major variables influencing flotation thickening given by Burd (17) are as follows: (1) pressure; (2) recycle ratios; (3) feed solids concentration; (4) detention period; (5) air to solid ratio; (6) type and quality of sludge; (7) solids and hydraulic loading rates; and (8) use of chemical aids.

Generally speaking, greater float concentration is obtained as pressure is increased. However, depending on the type of the sludge and other parameters, a critical pressure exists beyond which air pressure breaks up fragile flocs. Optimum value of air recommended by Mayo (79) is 0.03 $ft^3/ft^2/min$. Katz (80) has observed that increase in the recycle ratio resulted in a significant increase in the rate of rise of particles, as shown in Figure 13. Recycle ratio and feed solids are interrelated. It has been observed that dilution of the feed sludge to a lower concentration increased the concentration of the floated solids (71). Detention period has also been found to influence the concentration of floated solids. Data presented by Katz (80) as shown in Figure 14 supports this fact.

The effect of air-to-solids ratio on the concentration of floats was investigated by Ettlet (78). As shown in Figure 15, increase in air-to-solids ratio caused increase in floated solids production. Because of rapid separation of solids from the sewage, higher loading can be

Figure 12

Rate of Rise of Floated Solids Interface(77)



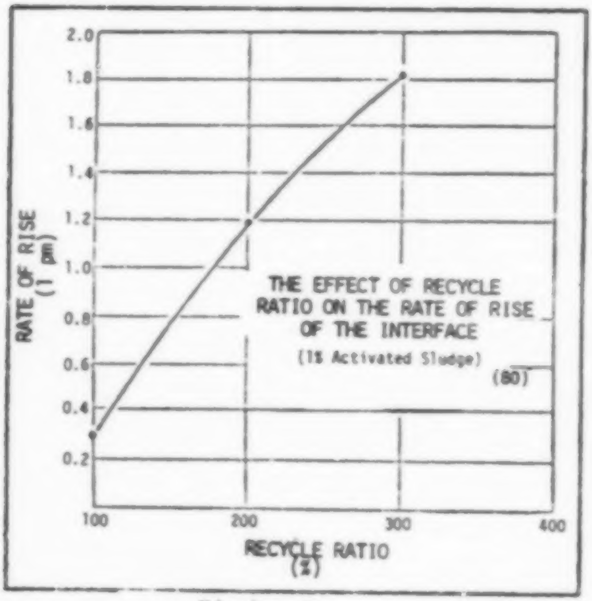


Figure 13

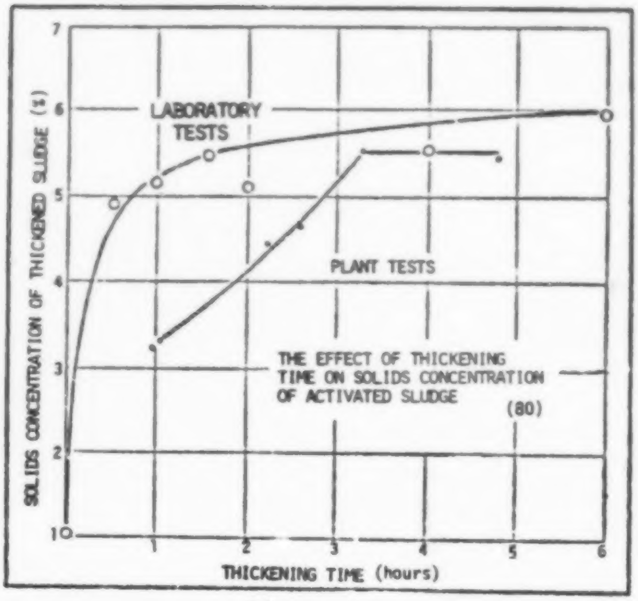
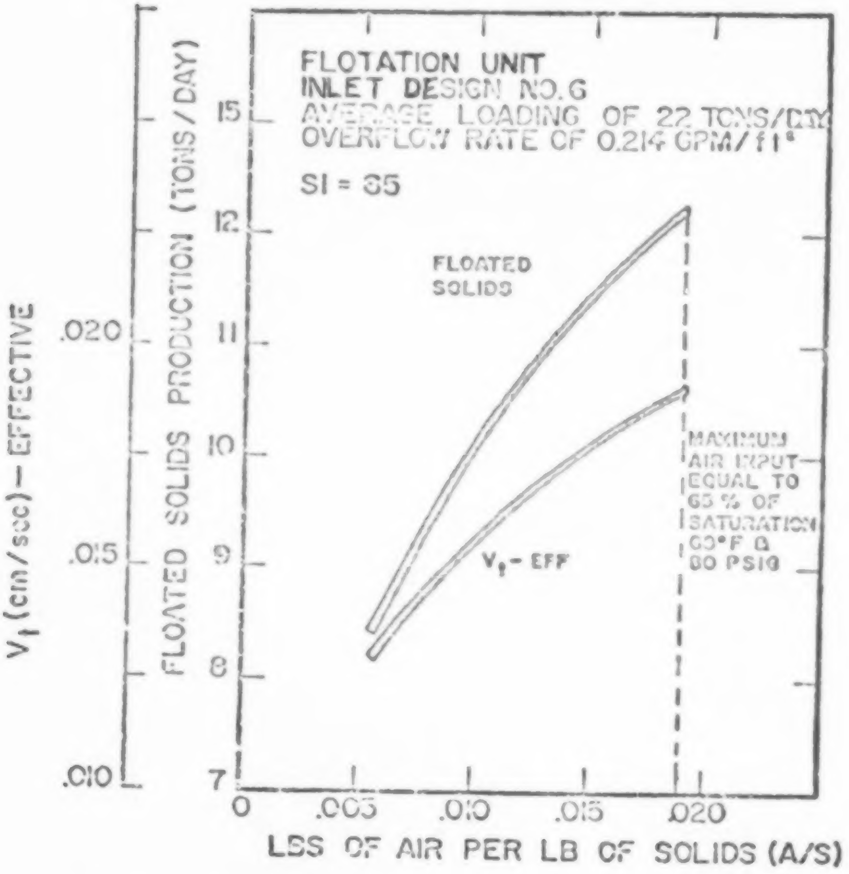


Figure 14

Figure 15

Effect of Air Content on Floated Solids Production and Effective Terminal Velocity at Constant Overflow Rate(78)



used. However, higher loadings may impair the performance of the thickening unit. Typical solids loading values are shown in Table 32.

TABLE 32

Loading of Dissolved-Air Flotation Units(14)

Type of Sludge	Loading, lb/sq ft/day
Activated (mixed liquor)	5-15
Activated (settled)	10-20
50% primary + 50% activated (settled)	20-40
Primary only	to 55

Centrifuge Thickening

Centrifugation of sludge for thickening and dewatering purposes has long been practiced in wastewater treatment plants. When centrifugation is employed for sludge thickening the purpose is to reduce the sludge volume to a point where the sludge is still fluid and can be pumped easily. Bradney and Bragstad (81) are among the first investigators reporting on the subject. Activated sludge containing a solids content of 0.5% to 0.8% was thickened to a concentration of 7%. An extensive investigation in the application of centrifugation was made by Ettelt and Kennedy (82) in the Chicago Sanitary District, where the objective was to thicken the waste activated sludge. Results showed that application of centrifugation for sludge thickening up to 7% was feasible although operation problems were noted. Centrifuge performance was noticed to improve when a mixture of activated sludge and primary sludge was used. The solids concentration obtained reached 9.8%. Further, the tests were carried out for various liquid levels in the centrifuge. It was observed that activated sludge was thickened to 16%, but the solid recovery was unsatisfactory, as shown in Figure 16. They have also used cationic polyelectrolytes for conditioning and have reported very satisfactory results, as shown in Figure 17.

SLUDGE STABILIZATION

The main objectives for application of treatment processes on wastewater sludge is to stabilize or sterilize the sludge and reduce its volume for the subsequent unit processes and final disposal. Methods

Figure 16

Decrease in Recovery with Corresponding Increase in Solids Concentration from Lowering Liquid Level(82)

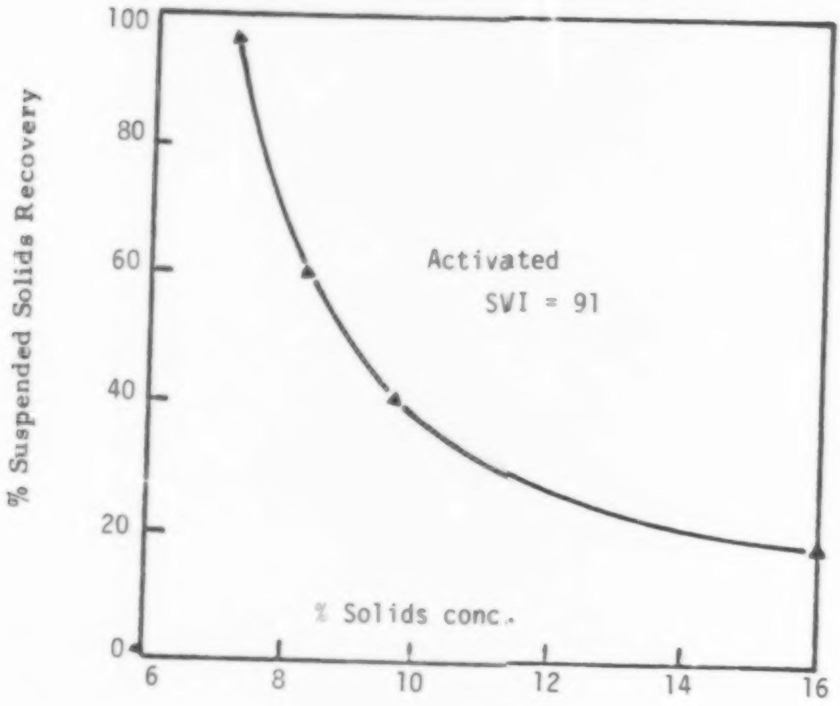
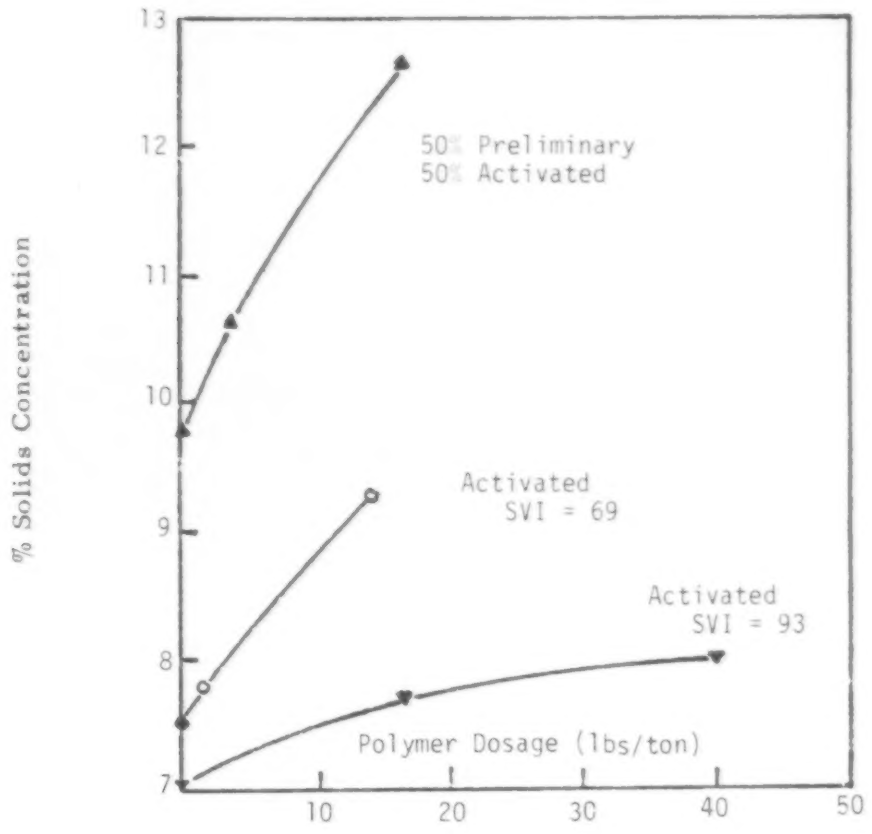


Figure 17

Effect of Chemical Addition on Solids Concentration by Concurrent Centrifuge at 90% Solids Recovery[(82)]



applied for stabilization of wastewater sludges include: (1) anaerobic digestion; (2) aerobic digestion; (3) composting; (4) lagooning; (5) heat treatment; (6) chemical stabilization; and (7) other processes.

Anaerobic Digestion

Anaerobic digestion of sludge involves decomposition of organic and/or inorganic material in the absence of free oxygen. The anaerobic digestion of organic matter occurs in two separate stages, called liquefaction and gasification stages. The end products of the first stage are utilized in the second stage as fast as they are produced. The general biochemical reactions for the entire process are summarized (83) as follows:

First stage reactions:

$$\begin{matrix}\text{Complex Organic}\\ \text{Matter}\end{matrix} \xrightarrow{\begin{matrix}\text{Facultative and}\\ \text{Anaerobic Bacteria}\end{matrix}} \begin{bmatrix}\text{Simple Sugar,}\\ \text{peptides, glycerol,}\\ \text{fatty acids, amino acids}\end{bmatrix}$$

$$\xrightarrow[\text{(Acid forming bacteria)}]{\begin{matrix}\text{Facultative and}\\ \text{Anaerobic Bacteria}\end{matrix}} \begin{bmatrix}\text{Organic Acids}\\ \text{Aldehydes}\\ \text{Alcohols}\\ CO_2 + H_2\end{bmatrix}$$

Second stage reactions:

$$\begin{bmatrix}\text{Organic Acids}\\ \text{Aldehydes}\\ \text{Alcohols}\\ CO_2 + H_2\end{bmatrix} + \begin{bmatrix}\text{Soluble}\\ \text{Nitrogenous}\\ \text{Compounds}\end{bmatrix} \xrightarrow{\begin{matrix}\text{Methane forming}\\ \text{Bacteria}\end{matrix}}$$

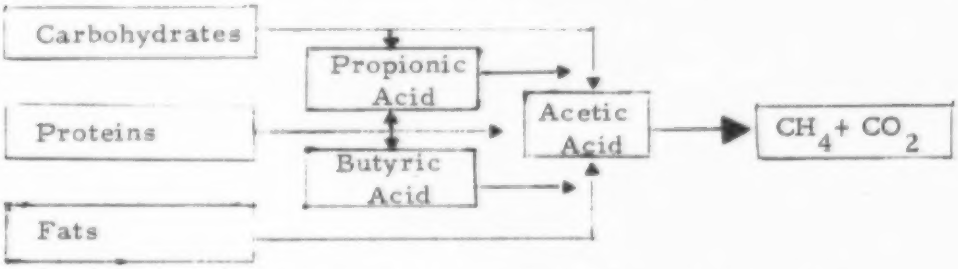
$$\begin{bmatrix}\text{Amines}\\ \text{Ammonia}\\ \text{Acid Carbonates}\\ CO_2,\ CH_4,\ H_2,\ \text{N2}\end{bmatrix} + \begin{bmatrix}\text{Mercaptains}\\ \text{Indole}\\ \text{Skatol}\\ H_2S\end{bmatrix}$$

and

$$\begin{bmatrix}\text{Amines}\\ \text{Ammonia}\\ \text{Acid Carbonates}\\ CO_2,\ CH_4,\ H_2,\ N_2\end{bmatrix} \xrightarrow{\begin{matrix}\text{Methane forming}\\ \text{Bacteria}\end{matrix}} \overset{\uparrow}{CH_4} + \overset{\uparrow}{CO_2} + \begin{bmatrix}\text{Very small}\\ \text{amount of}\\ \text{other gases}\end{bmatrix}$$

The flow-sheet diagram of the two stages involved in the anaerobic digestion process is given in Figure 18.

Figure 18
Flow Chart Diagram of Anaerobic Digestion Process



Decomposition of organic material is completed by two groups of microorganisms. Responsibilities of the first group are the hydrolysis and fermentation of the complex organic compounds to simple organic acids such as propionic, butyric, and acetic acids. The microorganisms in this group are both facultative and anaerobic bacteria, collectively called acid forming bacteria. Responsibilities of the second group of microorganisms is to convert the organic acids formed in the first stage to methane gas and CO_2. These bacteria are strictly anaerobic and are called methane forming bacteria. These bacteria have a very slow growth rate. Since complete decomposition occurs in this stage, anaerobic digestion generally takes a long time.

The main purpose of sludge digesting is to stabilize the sludge and make it fit for final disposal. Volume reduction and byproduct (gases) recovery are considered to be insignificant when compared with the conversion of raw materials such as fats, carbohydrates, and proteins into a stable and acceptable form.

Other reported objectives include: reduction of pathogenic organisms; production of more easily dewatered solids; volume reduction by concentrating the remaining solids to a dense sludge; and homogenizing sludge solids to facilitate subsequent handling steps (17).

Sludge digestion is the oldest method used for sludge stabilization. Burd (17) stated that "there is a trend to systems designed around raw sludge handling but digestion will continue to be popular, particularly at small sewage treatment plants and in large coastal cities; digestion permits inexpensive land and ocean disposal at these locations."

Factors effecting digestion of wastewater sludge include: sludge type and the volatile content of the solids; digester temperature; digestion detention period; feed sludge concentration; degree of digester mixing; digester loading rates; and presence of toxic materials. Volatile content of the sludge is an important factor. Generally the higher the volatile content of the sludge the better the digester efficiency. Temperature is an important factor influencing the rate of growth of bacteria. As the temperature increases, the minimum cell residence time of the bacteria in the digester is equivalent to the hydraulic detention period of the sludge in the digester, an increase in temperature could cut down on the digester volume (14). The general temperature range in which optimum biological activities take place is the mesophilic range (85 to 95°F) and the thermophilic range (125 to 135°F), Figure 19, shows that biological activity is not a direct mathematical function of the temperature. However, the most common range of temperature used in the digestion of wastewater sludge is in the range of 80 to 95° F (83).

The pH and volatile acid production influence the digester performance. The most desirable pH range for biological life in a digester is between 6.6 and 7.4 with a maximum tolerable range of about 6.4 to 7.8 (83). A pH below 6.4 is indicative of a rise in the volatile acid concentration. Increase in volatile acid concentration in turn suggests that the methane forming bacteria are not utilizing the volatile acids as fast as they are produced as the result of the first stage reaction. A low pH and a correspondingly high volatile acid concentration is referred to as an unbalanced digester. However, investigators (84) have taken issue by debating this theory. In general, most investigators feel that the volatile acid concentrations are a critical indicator of the state a digester is in, and the pH control is of the utmost importance. Low pH can be very toxic to the digesting process.

Presence of toxic material can hinder digester operation. At low pH, ammonia (NH_3 is usually found in the digester) is converted to NH_4^+ (cation) and toxicity will take place. Heavy metals such as copper, nickel, zinc, iron and chromium VI also cause toxicity at specified concentrations. Toxicity of heavy metals is eliminated by addition of sulfides (below 200 mg/l). The heavy metal ions are precipitated out as sulfides. Other cations causing digester toxicity include Na^+, K^+, Ca^{++}, and Mg^{++}. Synthetic detergents (ABS type) and soluble fatty acids have also shown toxicity at a concentration range of 40-1000 mg/l (85). Four methods are

Figure 19

Temperature vs. Biological Activity(83)

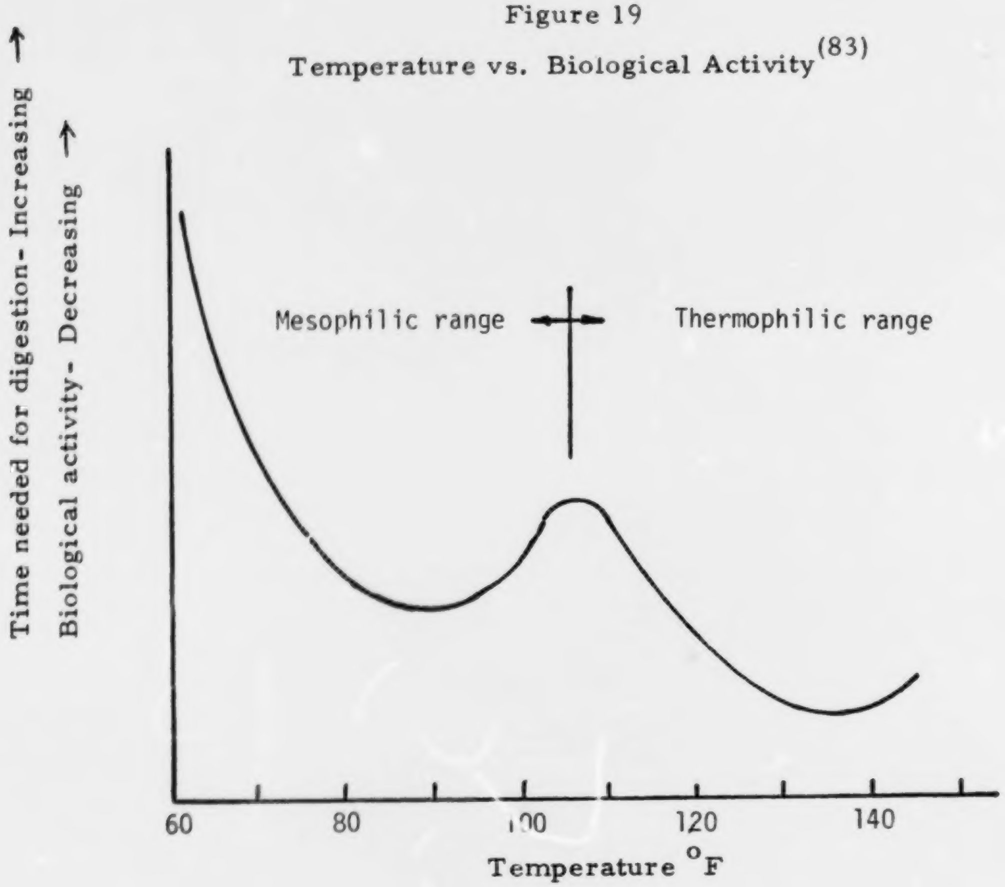


TABLE 33

Anaerobic Digesters - Design Criteria

	Conventional Digester	High-Rate Digester	Anaer. Cont. Process	Ref. #
1. Solids Loading	0.03	0.1-0.2	0.1-0.2	86
(lb vs/cu-ft/day)	0.04-0.1	0.15-0.40	--	17
2. Design Criteria (cu-ft/cap.)				
a) Primary Sludge	2-3	1-1/3 - 2	--	87
b) Trickling Filters	4-5	2-2/3 - 3-1/3	--	"
c) Activated Sludge	4-6	2-2/3 - 4	--	"
3. Digestion Retention Period	30-60 days	10-15 days	3-4 hrs	86
	39 days	14.5 days	--	

available for eliminating toxicity in an anaerobic digestion system (86). These methods include: (1) dilution of the waste itself, (2) precipitation of toxic material, (3) use of antagonistic ions, and (4) modification of the industrial process.

In high rate digesters, efficiency of operation depends on how well the digester content is mixed. Mixing not only brings the microorganisms in contact with the available food supply which increases the efficiency of microorganisms, it also keeps the concentration of biological end products uniform and prevents scum accumulation.

Performance and efficiency of a digester are greatly affected by the solids loading rate. In conventional digesters, loading rate is normally low and is added at a uniform rate. Loading in an unsteady rate or shock loading upsets the microorganisms drastically. In high-rate digesters and anaerobic contact process, loading rates are higher and continuous. Solids loading of different types of digesters, design criteria and digestion retention period required, as reported in the literature (17, 86, 87), are shown in Table 33.

Suhr and Brown (88) have done extensive work in evaluation of conventional digester versus high-rate digester. It was found that a high-rate digester can produce the same volatile solids reduction as the conventional digester with much lower digester capacity requirements. It was also observed that solid-liquid separation in the high-rate digester was much poorer than the conventional. Summary of their results is given in Table 34.

TABLE 34
Anaerobic Digesters - Design Criteria$^{(88)}$

	Conventional	High-Rate
Design cap.	3.0^{+} cu-ft/cap.	0.4
Digestion Period	30 days	16
Volatile solids reduction	65.9%	64.5
Digested sludge solids	6-9%	3.5-4

Numerous papers discuss the sludge digestion process, and compare the advantages and disadvantages of the conventional method with the high-rate method. In conclusion, one could say that proper operation of the digesters is an art and that no single rule of thumb exists that could be applied equally in any two digester units. Although it is a very effective process for sludge stabilization and perhaps sludge volume reduction, it is however an expensive process, contributes a vast quantity of nitrogen into the receiving water, and causes a lot of operational problems. Also, the resulting sludges have been shown to impose difficulty in the dewatering step.

Aerobic Sludge Digestion

Aerobic digestion is another method used for stabilizing the organic fraction of the sludge produced in wastewater treatment plants. The aerobic digestion process has not been used very extensively, as its application has been limited to small wastewater treatment plants. Aerobic digesters could be used to treat primary sludge, trickling filter sludge, and waste-activated sludge. To date, it has been extensively used in treating waste-activated sludge.

According to Loehr (89) aerobic digestion is a biological process having a long solids retention period, during which gross oxidation is completed in two stages:(1) direct oxidation of any biodegradable matter by a biologically active mass of organisms, and (2) oxidation of microbial cellular material by endogenous respiration. Whereas, endogenous metabolism depends on the living or active portion of the bacterial mass and becomes significant when food-limitation increases. Thus, bacterial growth and cell synthesis becomes minimal; furthermore,the bacteria is forced to utilize the food stored within their cells and endogenous metabolism is responsible for further decrease of the remaining sludge mass.

Reported (17,89) factors affecting design of aerobic digesters include: (1) rate of sludge oxidation, (2) sludge temperature, (3) oxygen requirements of the system, (4) sludge loading rates, (5) sludge age, (6) sludge solids characteristics, and (7) characteristics of the residue and supernatant liquid.

Oxidation rate of the sludge in an aerobic system is believed to be a function of many factors, such as sludge age, temperature, microbial content of the sludge, and the waste characteristics used to grow the sludge (89). The investigation of Lawton and Norman was reviewed by Loehr (89) and indicated that a high degree of correlation existed between percent volatile solids reduction and sludge age. Furthermore, Lawton and Norman used sludge age as a major parameter in obtaining volatile solids reduction in an aerobic digestion system.

In general, fresh sludge has a higher rate of volatile solids reduction as compared with old sludge which has already been oxidized partially prior to aerobic digestion. Loehr also reported that in an aerobic system, oxidation and sludge reduction are minimal during the winter, when temperatures are the lowest. Sludge age of about 15-20 days at 20°C is sufficient, whereas sludge age of 30-40 days is required if the temperature is 10°C.

The effect of retention time on percent volatile solids reduction in an aerobic system was investigated by Viraraghovan (90) and reveals that reduction of volatile solids is a function of retention time of up to 15 days as shown in Figure 20.

Burd has reported on the research work on aerobic digestion using a mixture of raw primary and waste activated sludge. As shown in Figure 21, at a temperature of 20°C, volatile solids reduction rate was very rapid during the first 12 days of detention period and was moderate thereafter. Figure 21 also reveals that as the temperature increased, the percent volatile reduction increased too.

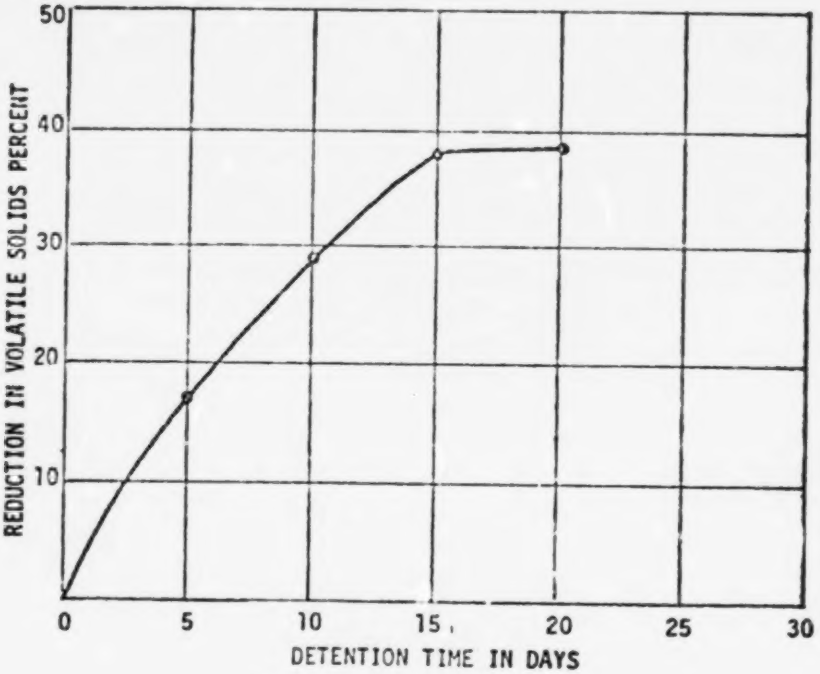
Change of digestion temperature affects the rate of metabolic activity of the microorganisms. Eckenfelder (91) has reported that a 10°C change in temperature will change the rate of metabolism of microorganisms by a factor of 2. Loehr (89) has reported that the effect of temperature is more significant at short detention periods (less than 15 days). This effect will decrease as the time lengthens and the loading rate decreases. Indeed, for long detention times temperature effect is insignificant because digestion is essentially completed at all temperatures. Loehr (89) has also reported the work of Jaworski and Lawton in connection with the effect of temperature on aerobic digestion of activated sludge. Volatile solids reduction of 3.2%/day at 15°C, 4.0%/day at 20°C and 4.5%/day at 35°C for the first ten days, and then 0.15%/day at 15°C, 0.1%/day at 20°C for the remainder of the study was reported.

It has been observed that aerobic digestion of activated sludge results in lowering the pH drastically. Values of pH as low as 4.5 have been reported (92) after 15 days of sludge digestion. Randal (93) et al conducted a comprehensive investigation of the effects of low pH environment on the aerobic digestion process with respect to volatile solids destruction and sludge dewaterability, both on laboratory and pilot-plant scales. The conclusions on the sludge made are as follows:

1. The destruction of activated sludge solids during aerobic digestion is a strong direct function of the initial volatile solids fraction of the sludge.
2. The influence of mixed liquor pH on solids destruction is small when compared to variation with initial volatile solids fraction.
3. The final mixed liquor pH value achieved during aerobic digestion is primarily a function of the nature of the specific sludge being digested.
4. Substantial activated sludge solids destruction can occur during

Figure 20

Volatile Solids Reduction- Effect of Detention Time(90)



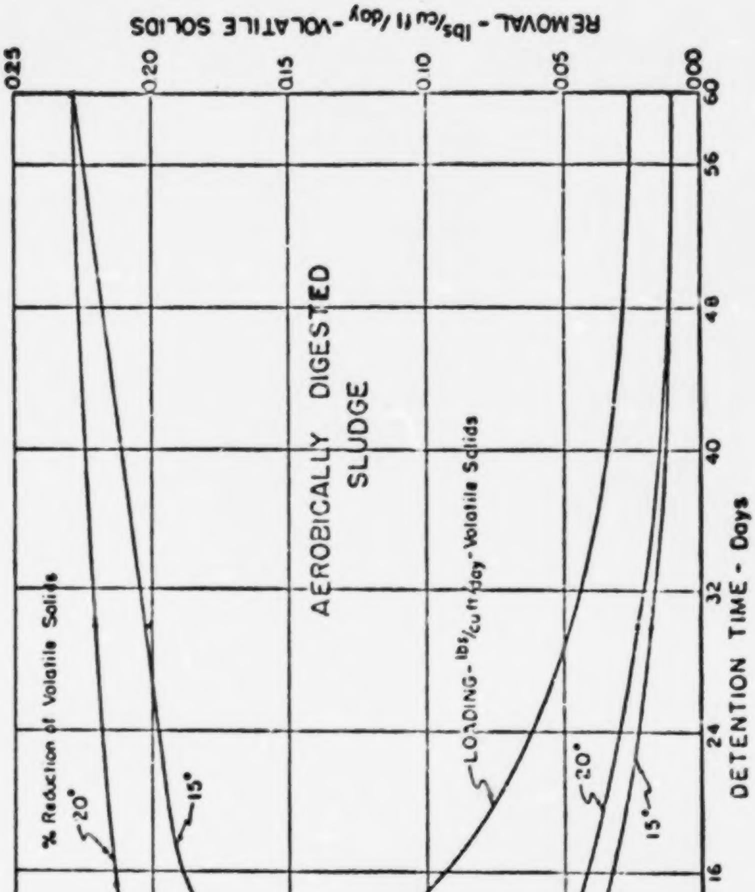

AEROBICALLY DIGESTED SLUDGE
REMOVAL - lbs/cu ft/day - VOLATILE SOLIDS
.025
.020
.015
.010
.005
.000
% REDUCTION OF VOLATILE SOLIDS
50
40
30
20
10
0
DETENTION TIME - Days
8
16
24
32
40
48
56
60
% Reduction of Volatile Solids
20°
15°
35°
LOADING - lbs/cu ft/day - Volatile Solids
20°
15°
35°
Removal of Volatile Solids lbs/cu ft/day

Figure 21(17)

aerobic digestion at mixed liquor pH levels as widely separated as 3.5 and 9.5.

5. The optimum pH range for aerobic digestion from a solids destruction viewpoint is from 6 to 7.
6. The pH of the mixed liquor during aerobic digestion has a strong effect on the levels of nitrates and phosphates in the supernatant. Extreme pH values completely inhibit nitrate formation and cause extremely large releases of soluble phosphorus.
7. Large protozoa populations can produce very significant increases in waste activated sludge settleability, filterability and drainability during aerobic digestion even at very low pH levels.

Advantages claimed (17, 89, 90) for an aerobic digestion system are as follows: (1) volatile solids reduction obtained from aerobic digestion is comparable to that obtained from anaerobic systems; (2) aerobically digested wastewater sludge is humus-like and has no disagreeable or objectional odor, thus, lagoons can be used for final disposal; (3) supernatant liquor has lower BOD concentration; (4) product sludge has excellent dewatering characteristics; (5) capital costs are generally low; (6) it is a relatively problem-free operation; and (7) product sludge contains more basic fertilizer value. The major disadvantage of the aerobic digestion process is the high power cost associated with the required oxygen. Lack of methane gas production and variation of the performance as the temperature changes are believed to be the minor disadvantages.

Composting of Sludge

Aerobic composting of sewage sludge is a biological process. It can be defined as decomposition of organic waste by aerobic thermophilic organisms to produce a stable humus-like material. The byproducts of this treatment process are carbon dioxide, water and heat. The compost produced can be used as soil conditioner or fertilizer depending on its nutrient content.

Composting of wastewater sludge and other solid wastes has been extensively practiced in Asia and Europe for centuries with the products formed being used as soil conditioner and fertilizer. Composting of sludge and refuse has received special attention in Europe for the past thirty years because of the enactment of a water pollution program which has resulted in the formation of tremendous quantities of sludge and refuse. Also, there has been a shortage of chemical fertilizer. Composting of community solid wastes in the U.S. was first studied by the University of Californic during the years 1950-1952. It was concluded that composting should be considered as a means of disposal and reclamation for municipal refuse (94). Beginning in 1953, Wiley and others of the Public Health Service, Communicable Disease Center, (95, 96, 97), conducted extensive research in composting of ground refuse and refuse-sludge mixtures on a laboratory scale project at Savannah, Georgia, and in pilot plant projects at Chandle, Arizona. After ten years of studies, they concluded that composting of municipal refuse with or without sludge is a feasible and a sanitary method of treatment. In the early 1960's, compost plants were built primarily for sale of compost as a substitute for chemical fertilizer. However the sale of compost did not appear to be profitable and most plants closed down after two or three years of operation.

In recent years, composting of sludge mixed with refuse has been reconsidered in the U.S. due to the higher cost and other problems associated with conventional methods of sludge disposal.

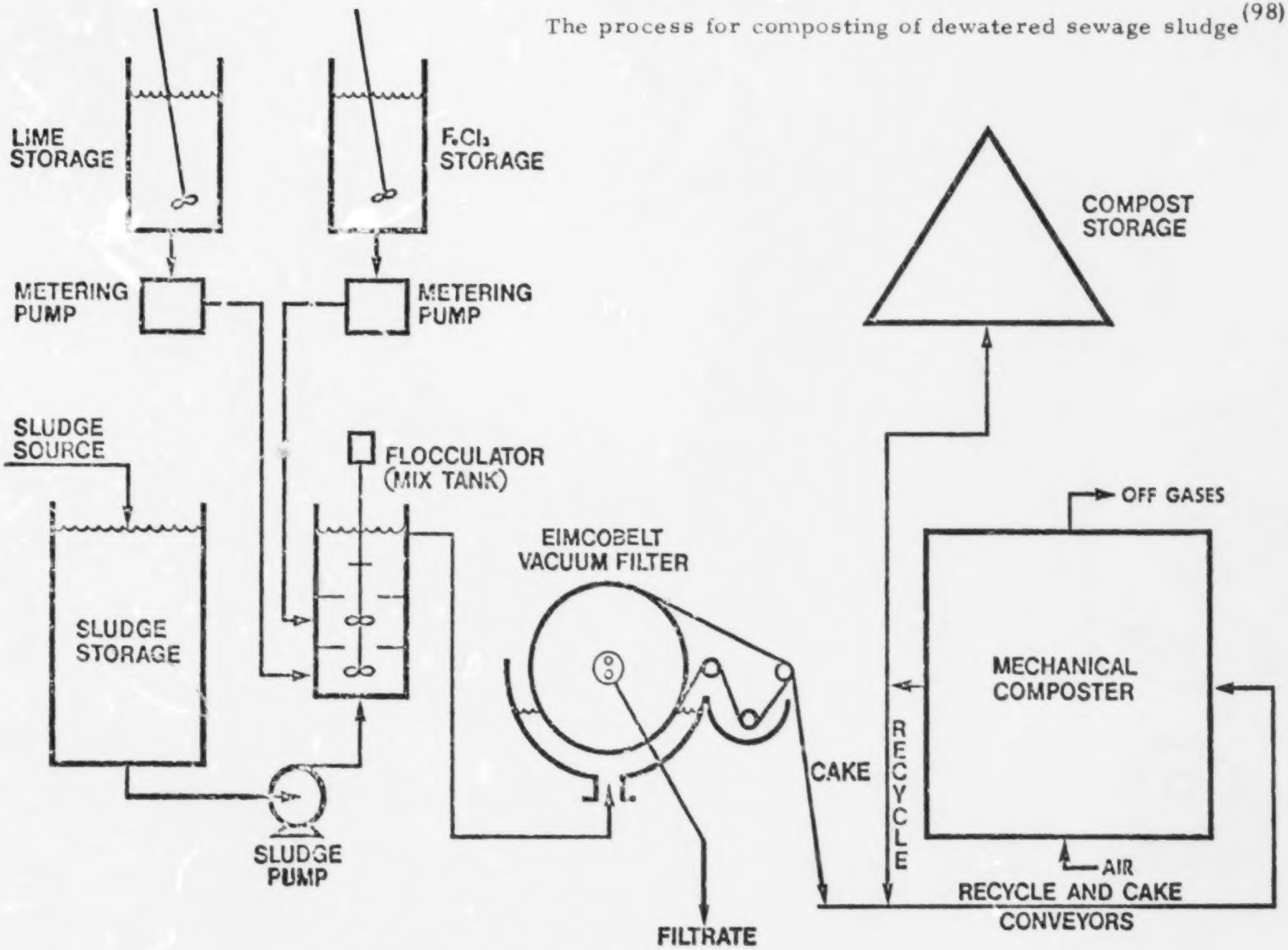
Since composting of sewage sludge is an aerobic biological process, it is necessary to provide an adequate method for supplying oxygen and thorough mixing of the sludge during the composting operation. This is required in order to obtain an efficient odor-free sludge treatment. Composting methods used include indoor (mechanical), and outdoor (windrows and bins) processes. In the mechanical composting process of sewage sludge there are are three phases. These are: (1)dewatering of the sludge, (2) composting, and (3) final curing. A flow diagram of a mechanical composting process is shown in Figure 20.

Dewatering of the sludge accomplishes the following: (1) reduces the volume and (2) obtains an optimum moisture content required for proper composting. Mechanical dewatering processes such as vacuum filtration and centrifugation are frequently employed along with chemical conditioning agents which enhance the dewaterability of the sludge. The cake moisture content produced often ranges from 70 to 80 %.

In the second phase, dewatered sludge is mixed with recycled compost from the composter to accomplish the following purposes: (1) to adjust the moisture content of the feed sludge, and (2) to seed the incoming sludge with microorganisms. The mixture of filter cake and recycled compost is then transferred to the mechanical composter, where it is continuously mixed and aerated. The temperature of the mix during composting averages

Figure 20

The process for composting of dewatered sewage sludge(98)


LIME STORAGE
FeCl$_3$ STORAGE
METERING PUMP
METERING PUMP
COMPOST STORAGE
SLUDGE SOURCE
FLOCCULATOR (MIX TANK)
OFF GASES
EIMCOBELT VACUUM FILTER
SLUDGE STORAGE
MECHANICAL COMPOSTER
CAKE
RECYCLE
SLUDGE PUMP
AIR
RECYCLE AND CAKE CONVEYORS
FILTRATE

about 140°F. The heat is produced through biological action.

In the third phase, the end products obtained from the composter are stored for curing.

The factors which affect the sludge composting process are: (1) mixing, (2) moisture content, (3) percentage of recycled compost, (4) aeration, and (5) temperature and pH. Continuous mixing of the sludge in the composter is essential since it keeps the bed loose and prevents air channeling, and supplies the microorganisms with adequate air (98). The moisture content of compost depends upon the feed cake moisture content, retention time within the composter, and the rate of aeration and mixing. Moisture content of the feed to the composter depends upon the moisture content of the filter cake and the percentage of the recycled compost and its moisture content.

Observations have shown that efficient composting is obtained when the moisture content of the mix during composting ranges from 25 to 40%. Biological action of the microorganisms was greatest at moisture contents of 20 to 30%. Below 15% moisture or above 40% moisture biological activity slowed down significantly (98). With a moisture,content above 40%, mixing and other operational problems occur. When the moisture content is below 15%,dusting problems arise (98).

Optimum conditions for composting are obtained by recycling the compost and thoroughly mixing. The affect of recycling is indicated in results obtained which reported that a 45% solids reduction was possible with a 1.5 recycle ratio, while only 18% solids reduction was obtained using 1.0 recycle ratio. Both were for a seven day retention time (98). Recycling of the compost results in an increase in the temperature of 10 to 20°F and changes the pH of the feed from 10-11 to 7.

A temperature in the thermophilic range of greater than 110°F has been shown to produce a more rapid rate of decomposition than those in the mesophilic range (<110°F). It has been reported (14) that 140°F is an optimum temperature, and is adequate for destruction of most pathogens.

Aeration of the compost has two functions: (1) it provides a means for rapid evaporation of excess moisture fed to the compost, and (2) it maintains aerobic conditions. According to Shell and Boyd (98) the first step in composting of dewatered sludge is moisture reduction through evaporation (reduction of 80 to 90%) followed by biological destruction of volatile solids. An air flow rate of 0.25 scfm-ft is believed to be adequate.

Physical and chemical characteristics of a mechanically composted sewage sludge (combined primary and trickling filter) are presented in Table 35.

TABLE 35

Physical and Chemical Characteristics of Wastewater Sludge Compost(98)

Total Kjeldahl nitrogen (% N by weight)	2.21
Total nitrate (% NO_3 by weight)	0.01
Total phosphorus (% P_2O_5 by weight)	2.16
Total potassium (% K_2O by weight)	0.27
pH	6-6.5
Bulk Density (lb/cu ft)	48.2
Moisture (% by weight)	20-35
Color	Dark brown
Odor	Musty

Wiley (99) in discussing composting of wastewater sludge with refuse solids has stated that "treatment of sewage sludge with refuse or other solid wastes offers several advantages over their separate treatment by conventional processes. These advantages include enhancement of the composting process, reductions in problems of sludge processing and disposal, and reduction in processing costs."

Composting of sewage sludge mixed with refuse has been investigated very thoroughly, both by mechanical composters and outdoor composting. It is believed that addition of wastewater sludge indeed enhances the composting operation for such reasons as: (1) controlling the moisture content in the composting mixture; (2) providing a seed material necessary for initiation of biological action; (3) enhancing the nutritious values of the final compost; and (4) providing a means to control the C/N ratio. Preparation of refuse-sludge moisture for composting requires sorting of the refuse and mixing of sludge with refuse. The sorting has the purpose of removing the metals, rags, and other material which would adversely affect the composting operation and alter the quality of the end product.

It appears that the parameters affecting sludge-refuse composting operation are essentially the same as those used for mechanical sludge composting. The moisture content of the compost mixture has been recommended (100) not to exceed 50 to 60%. Gothard (101) has noted that a sludge with a dry refuse ratio of 0.7 to 1.1 is required to produce an optimum moisture content of 65%. The recommended C/N ratio that is essential for optimum activity of microorganisms ranges from 25 to 30 (100).

Successful composting of digested sludge with straw, sawdust, and wood shavings under favorable climatic conditions has also been reported (102).

Lagooning of Sludge

Sludge lagooning is the most economical method of treatment and disposal, particularly for smaller plants and where land is relatively inexpensive. A sludge lagoon is essentially a large shallow unheated digester. It may be a natural or artificial depression in the ground. Sludge lagoons have been used for a variety of purposes such as for thickening, storage, digestion, drying and final disposal of sludge. When a lagoon is used for digestion of raw sludge, odor and insect breeding may be problems. When a lagoon becomes filled with digested sludge, it is either abandoned or drained and the digested sludge is excavated. Some of the design parameters commonly used are ; (1) land area, (2) climate, (3) subsoil permeability, (4) lagoon depth, (5) lagoon-sludge loading rate, and (6) sludge characteristics and types. Several investigators (6, 45, 103) have made studies on lagoon design parameters, dewatering rate, etc. Typical loading rates reported (17) are presented in Table 36.

TABLE 36(17)

Sludge Types	Loading Rate
Raw (using lagoon as digester)	6 lbs/yr/cu-ft of lagoon cap.
Undigested (using lagoon for dewatering)	2.2 to 2.4 lb/yr/cu-ft of lagoon cap.
Digested (using lagoon for dewatering)	1.7 to 1.84 lb/30 days/ sq-ft of lagoon surface area

Heat Treatment

Heat treatment of the wastewater sludges has gained popularity in recent years. This process takes advantage of the combined properties of heat and pressure. When sludge is heated at high temperatures under pressure, the gel-like structure of the sludge is destroyed and the bound water is liberated. The resulting product is sterilized, deodorized and readily dewaterable (40, 41, 108).

Major processes used for heat treatment of wastewater sludges include: (1) Zimpro process, (2) Porteous process, and (3) Farrer system.

Application of the Zimpro process in treatment of wastewater sludge is growing rapidly. Table 37 indicates municipal wastewater treatment plants equipped with this process, or additions utilizing it are under construction. A schematic of this process is shown in Figure 23. Operation of the process includes these following steps: (1) sludge is ground up and pumped to a sludge holding tank, (2) compressed air is introduced into the sludge and the mixture is brought to an operating temperature above 350°F by heat exchange and direct steam injection, (3) the heated conditioned sludge is cooled by heat exchange with the incoming sludge, (4) gases are separated and released through a catalytic afterburner or equivalent odor control device, (5) conditioned sludge is concentrated by settling and dewatered by filters, centrifuge or on drying beds, and (6) liquor, readily biodegradable, flows to secondary plants or to separate treatment units. Short reaction time assures minimum color and BOD.

Figure 23
Schematic flow diagram of the Zimpro wet-air oxidation system (111)

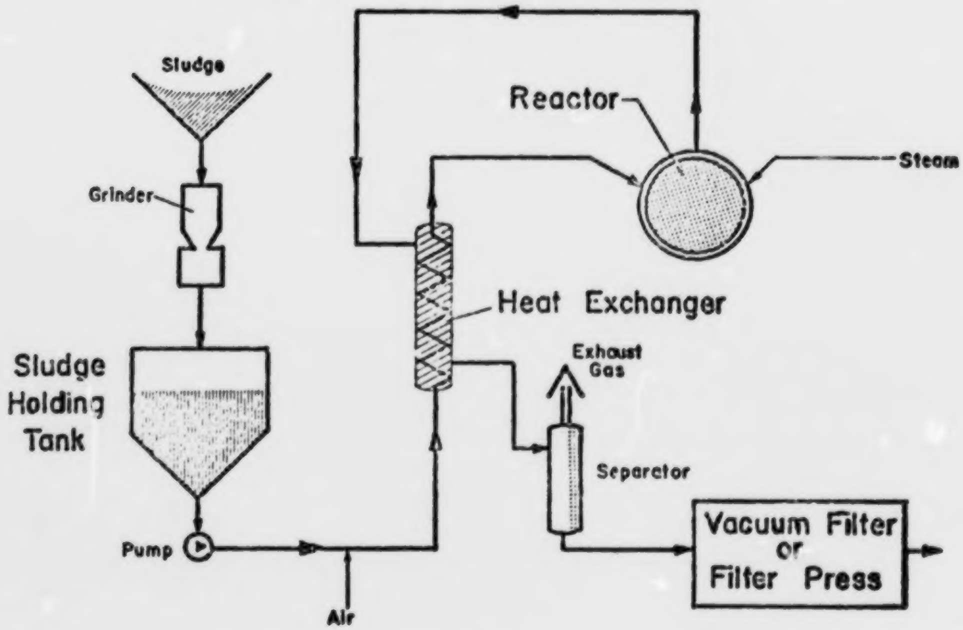


TABLE 37

ZIMPRO THERMAL SLUDGE CONDITIONING INSTALLATIONS
(UNITED STATES ONLY)

PROJECT	ENGINEER	TYPE OF PLANT**	TYPE OF WASTE	TONS OF SOLIDS PER DAY	GALLONS PER MINUTE	INITIAL OPERATION
Lower Bucks County Joint Municipal Authority Levittown, Pennsylvania	Paul X. Blattler, Managing Engineer LBCJMA	LO	Primary & Activated Sludge and Digested Sludge	7.36	20.0	1967 & 1970
Cannon Mills Kannapolis, N. C.	Engineering Department Cannon Mills	LO	Activated & Primary Sludge (Textile Plant Waste and Domestic Sewage)	15.0	50.0	1967
Valley Sanitary District Indio, California	Koebig & Koebig, Inc.	LO	Primary & Activated Sludge	6.4	30.0	1969
Rothschild, Wisconsin	Becher-Hoppe	LO	Primary & Activated Sludge	1.44	6.7	1969
Wausau, Wisconsin	Becher-Hoppe	LO	Primary & Activated Sludge (Raw or Digested)	6.75	37.0	1970
Millville, N. J.	Albert C. Jones, Assoc.	LO	Primary & Activated Sludge	8.7	36.0	1970
Defiance, Ohio	Jones & Henry Engineers, Limited	LO	Primary & Digested Sludge	4.0	12.0	1970
Denton, Texas	Freese, Nichols & Endress	LO	Primary & Digested Sludge	6.0	33.0	1970
Fort Lauderdale, Florida	Philpott, Ross & Saarinen	LO	Primary & Activated Sludge	15.0	61.0	1971
West Memphis, Arkansas	Albert Switzer & Assoc., Inc.	LO	Primary & Activated Sludge	2.7	16.3	1970
Jeffersonville, Indiana	Moore & Heger	LO	Primary & Activated Sludge	4.25	23.0	UC*
Siloam Springs, Ark.	McGoodwin, Williams & Yates, Inc.	LO	Primary Sludge & Trickling Filter Humus	5.0	14.0	1970
Gloversville-Johnstown, New York	Morrell Vrooman Engineers	LO	Primary & Trickling Filter & Activated Sludge	30.6	100.0	UC*

TABLE 37 cont'd.

ZIMPRO THERMAL SLUDGE CONDITIONING INSTALLATIONS
(UNITED STATES ONLY)

PROJECT	ENGINEER	TYPE OF PLANT••	TYPE OF WASTE	TONS OF SOLIDS PER DAY	GALLONS PER MINUTE	INITIAL OPERATION
Kalamazoo, Michigan	Jones & Henry Engineers, Limited	LO	Primary & Activated Sludge	97.5	3-125	1971
Bedford Heights, Ohio	Hedrick-Cox-Dancull	LO	Primary & Activeted Sludge	8.0	26.0	UC•
Cambridge, Maryland	Benjamin E. Beavin Co.	LO	Primary & Activated Sludge	16.0	65.0	UC•
Amsterdam, New York	O'Brien & Gere	LO	Primary & Activated Sludge	12.3	50.0	UC•
Mayfield, Kentucky	Allen & Hoshall	LO	Primary & Activated Sludge	2.3	10.0	1971
Terre Haute, Indiana	Henry B. Steeg & Assoc.	LO	Digested Sludge	12.0	39.0	UC•
Newport, Tennessee	Allen and Hoshall	LO	Primary Activated Sludge	4.9	20.0	1971
Midland, Michigan	McNamee, Porter & Seeley	LO	Raw Primary & Trickling Filter	16.32	33.3	UC•
Columbus, Ohio	Bonham, Grant & Brundage	LO	Primary & Activated Sludge (Raw or Digested)	49.0	200.0	UC•
North Olmsted, Ohio	Floyd G. Browne & Assoc., Ltd.	LO	Primary & Activated Sludge (Raw or Digested)	10.4	34.0	UC•
Maumee River-Lucas County, Ohio	Finkbeiner, Pettis & Strout, Ltd.	LO	Waste Activated Sludge	10.0	32.6	UC•
Speedway, Indiana	Henry B. Steeg & Assoc.	LO	Digested Primary & Activated Sludge	7.5	40.8	UC•
Canton, Ohio	Floyd G. Browne & Assoc., Ltd.	LO	Primary & Activated Sludge (Raw or Digested)	2-28.75	2-75.0	UC•

* Under Construction

** LO - Low Oxidation

TABLE 37 cont'd.

ZIMPRO THERMAL SLUDGE CONDITIONING INSTALLATIONS
(FOREIGN)

PROJECT	ENGINEER	TYPE OF PLANT*	TYPE OF WASTE	TONS OF SOLIDS PER DAY	GALLONS PER MINUTE	INITIAL OPERATION
Apeldoorn, Holland	City Engineering Dept.	LO	Primary and Activated Sludge	11.6	32.6	1969
Staz, Switzerland (St. Moritz)	Toscano-Bernardi-Frey Zurich, Switzerland	LO	Raw Primary and Activated Sludge	4.0	16.2	1970

From a plant operator's viewpoint, the Zimpro process offers many advantages, according to Mann (109). The advantages include: (1) reduction of detention time from weeks and days to minutes, (2) solids produced are more concentrated and much easier to dewater, (3) process is virtually free of upsets due to types of sludge and loading, (4) eliminates chemicals and increases production, and (6) the operator is not exposed to the sludge as a daily routine.

Advantages claimed for this process are that the resulting end products are: (1) dewaterable withour chemical conditioning by filters, centrifuges, or sand drying beds, (2) sterile residue of humus-like appearance, and (3) cake with a low moisture content (50 to 70 %) suitable for ultimate disposal by dumping or incineration without supplementary fuel. Furthermore, the total cost for the Zimpro process (including land, amortization, fuel, power, water, labor and maintenance) has been claimed to be less than the costs of chemicals alone when chemical conditioning is used (108). However, the cost for treating the supernatant is not included in the above total cost.

Figure 24 represents a schematic of the Porteous process used for wastewater sludge treatment. In this process sludge is preheated to about 320°F by passing it through a heat exchanger. Sludge is then discharged into the reactor, where the sludge is being heated at approximately 380°F and maintained at this temperature for about 30 minutes to an hour before it is discharged back into the heat exchanger and out from the system. Operating pressure may vary from 160 to 250 psi depending on the type of sludge being treated (37). The resulting end product is easily dewaterable; it can be dewatered to solids content of 40 to 60% without use of chemicals (14).

The advantages claimed for the Porteous process are basically the same as those outlined for the Zimpro process. The major difference between the two processes is that in the Zimpro process, air is introduced into the reactor, and it is not in the Porteous system. Table 38 indicates typical characteristics of liquor after heat treatment of sludge by the Porteous process (111).

The Farrer system is based on the same principles as the Porteous process. The Farrer Company, after purchasing the Porteous patents, modified the process to make these improvements: (1) overcome the odorous steam released, and (2) prevent short circuiting in the vessel-type reactor when heat treating continuously (156).

Figure 24

Schematic flow diagram of the Porteous Heat Treatment Process[111]

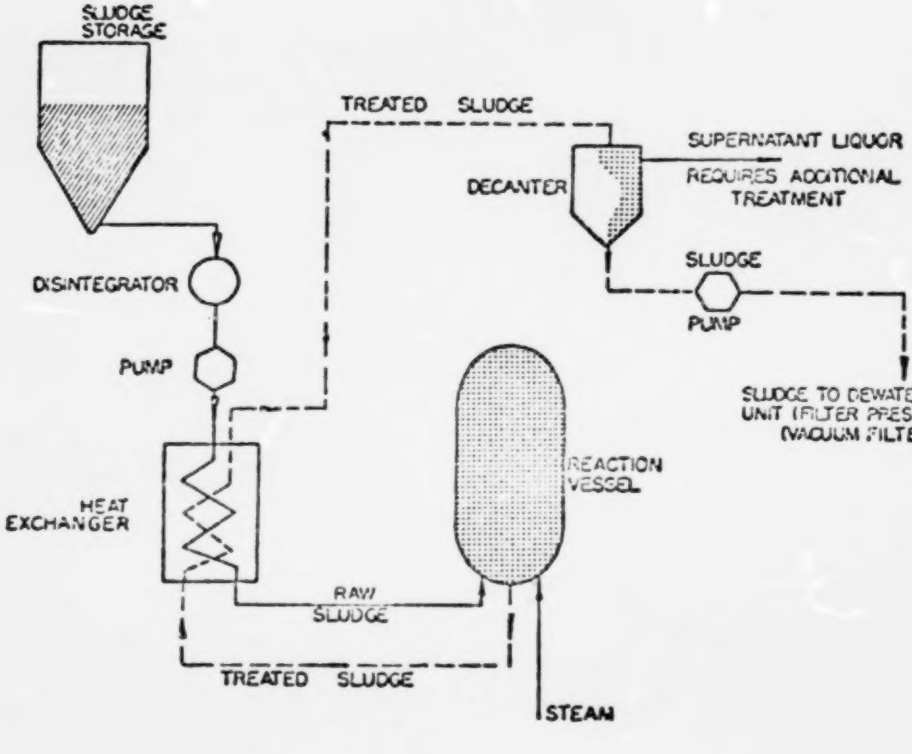

SLUDGE STORAGE
TREATED SLUDGE
SUPERNATANT LIQUOR
DECANTER
REQUIRES ADDITIONAL TREATMENT
SLUDGE
DISINTEGRATOR
PUMP
PUMP
SLUDGE TO DEWATERING UNIT (FILTER PRESS) (VACUUM FILTER)
REACTION VESSEL
HEAT EXCHANGER
RAW SLUDGE
TREATED SLUDGE
STEAM

TABLE 38

Characteristics of Liquor After Heat Treatment: Porteous Process(111)

	Heat-Treatment Liquor			Press Filtrate	
	Activated Sludge	All Sludges	Primary and Activated	Primary Sludge	Primary and Activated
Total solids (mg/l)	10,820	7,500	16,626	10,440	10,430
Suspended solids (mg/l)	--	--	197	--	--
BOD_5 (mg/l)	4,620	4,500	10,440	3,780	4,170
Organic nitrogen (mg/l)	1,110	410	1,440	150	504
Ammonia nitrogen (mg/l)	418	830	531	220	190

The Farrer system is a continuous sludge conditioning process in comparison to batch treatment of the Porteous process. Heat treatment of the sludge is a time-temperature relationship, where temperature ranges from 350-400°F and time varies from 20 to 30 minutes. Figure 25 shows a schematic of this system. The system consists of a thickener, disintegrator, heat exchanger, boilers, decanting and storage tank, and a dewatering device. Heating of the sludge is accomplished in the tube-type heat exchanger by indirect heat exchange using hot water through a closed loop. This is the major improvement over the Porteous process, in which steam is injected directly into the sludge.

Major advantages of this system over the Porteous process are claimed to be: (1) the need for sophisticated deodorizing devices is eliminated as there is no odorous steam released; (2) the feed volume to the reactor is not increased by condensed steam; and (3) since water is used in a closed loop, the need for continuous water supply and treatment is eliminated (156).

In reviewing other investigators papers, Balakrishnan et al (156) have reported that the filtration rate of domestic wastewater sludge has been improved drastically through application of heat treatment, with temperatures in excess of 130°C. When the temperature is raised between 160 and 190°C and held for 10 to 15 minutes, and then believed that a complete breakdown of the colloidal structure occurs. This resulted in a sludge that was 200 to 1000 times more filterable than untreated sludge and is 15 to 50 times more filterable than chemically conditioned sludge. Table 39 represents relative dewatering rates of sludge conditioned by different agents.

The major disadvantages of heat treatment include: (1) BOD of the filtrate is very high, ranging from 4000 mg/l to amost 20,000 mg/l, depending on the type of sludge being heated, and the amount of time spent in the reactor, (2) fuel requirement to produce necessary steam and temperature is high, and (3) need for separate treatment of the overflow liquor from the solid-liquid separation process and the filtrate of the dewatering system (111).

The atomized suspension technique has also been proposed for wastewater sludge treatment. This method is described as being a method for physical, thermal separation of dissolved or suspension solids from liquid, and subsequent chemical treatment of these solids by means of gas-solid reaction in a continuous operation (112).

Figure 25

Flow Sheet for the Dorr-Oliver Farrer System(156)

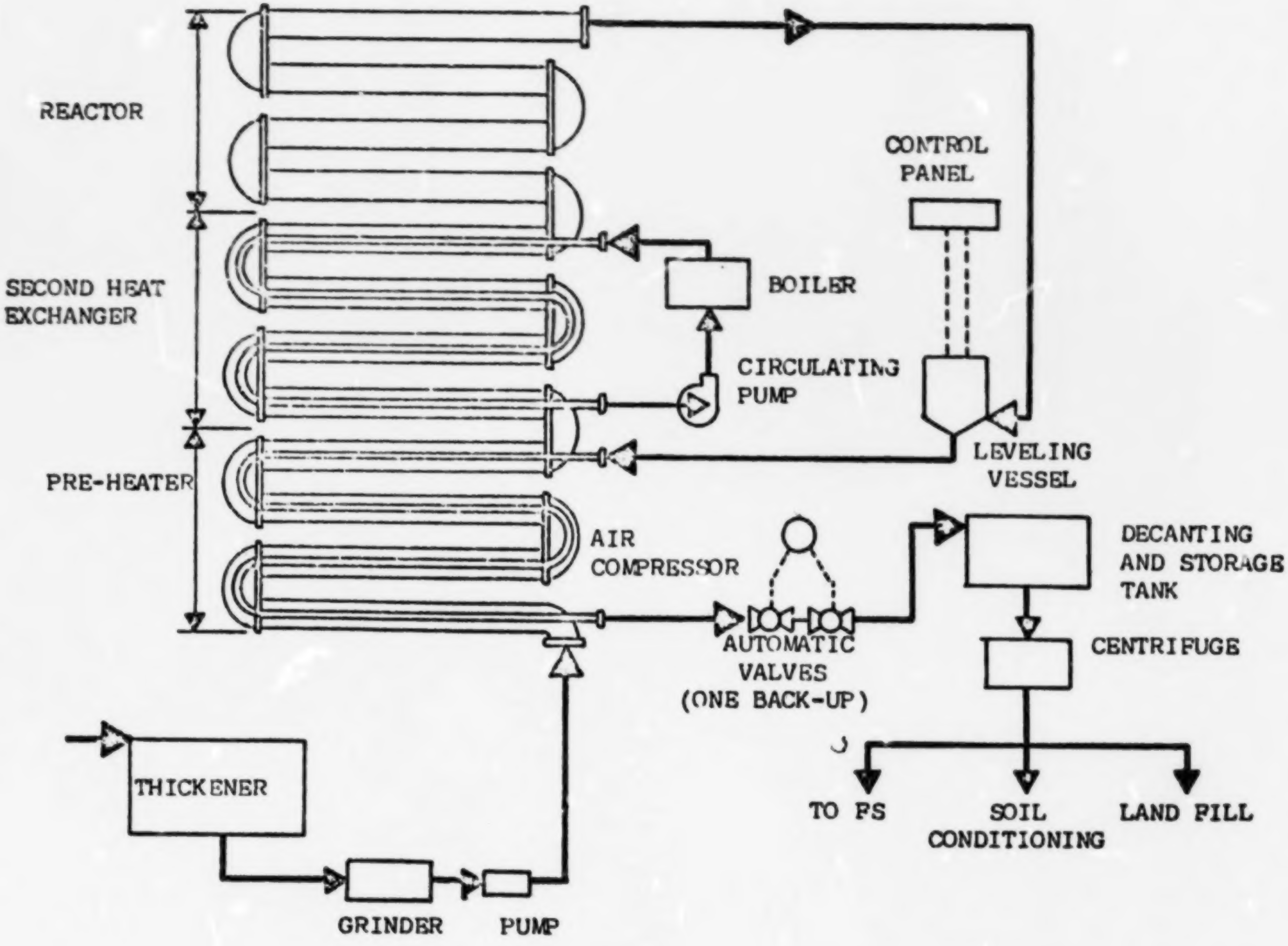

REACTOR
SECOND HEAT EXCHANGER
PRE-HEATER
CONTROL PANEL
BOILER
CIRCULATING PUMP
LEVELING VESSEL
AIR COMPRESSOR
AUTOMATIC VALVES (ONE BACK-UP)
DECANTING AND STORAGE TANK
CENTRIFUGE
TO FS
SOIL CONDITIONING
LAND FILL
THICKENER
GRINDER
PUMP

TABLE 39

Relative Dewatering Rates of Sludge Conditioned by Different Conditioning Agents(156)

Conditioning Agent	Relative Dewatering Rates	
	Primary Sludge	Secondary Sludge[1]
None	30	1
Sulfuric acid[2]	100	2
Aluminum sulfate[3]	200	10
Ferric sulfate[3]	300	15
Ferric chloride[3]	400	20
Lime[3]	1000	80
Heat treatment[4]	6000	1000

Note:
1. Mixed humus and activated sludge
2. At optimum pH value
3. At optimum dosage
4. One-half hour at 360°F

Chemical Stabilization of Sludge

Chemicals have also been applied to stabilize the sludge produced from wastewater treatment processes. The two chemicals most often used for this purpose are chlorine and lime. Both chemicals have been found to be very effective in microbial destruction. However, it has been reported that lime is less effective than chlorine in converting sludge to an inert material, but it is intrinsically softer and easier to handle (113).

Sludge stabilization by chlorine is also referred to as the chemical oxidation process. This process is generally performed using chlorine with low pressure.

According to Carnes (13) this process not only improves the dewaterability of the organic wastewater sludge, it has also been noted that attachment of chlorine gas bubbles to the solid particles causes flotation when applied to sand drying beds, resulting in improving the drainability significantly. The sludge solids discharged from this process are generally bleached to a light buff color. This method is not very effective in reduction of volatile content of the sludge; but, it is an effective method for the treatment of combined waste-activated sludge and oily sludge in which the heat causes the oil to float, making it easy to skim.

The literature reveals that numerous investigators (114, 115, 116) have studied the effectiveness of lime in reducing the microbial hazards in water, wastewater, and sludge. Lime was found to be very effective in sludge stabilization; however, most information available is qualitative and a minimum pH for satisfactory performance has not been established. Lime stabilization of the wastewater treatment plant sludge at Lebanon, Ohio was investigated by the Ultimate Disposal Research Group of NERC, EPA, Cincinnati, Ohio (113), recently. Results for the lime dose requirement are presented in Table 40. It was concluded that the lime demand is associated with the sludge solids and the wastewater itself. For raw sludge, the lime demand was low due to its high solids content. For chemical primary sludges (alum sludge and iron sludge) lime demand was not a function of solids content of the sludge. It is believed that higher lime demand for alum sludge was due to the fact that aluminum is amphoteric and reacts with $Ca(OH)_2$ to form calcium aluminate, where iron does not react in this way. Plant-scale test results shown in Table 41 indicated that typical enteric pathogens, Salmonella species and P. aeruginosa, are destroyed by lime treatment, and the organisms remaining after lime treatment appear to be non-pathogenic spore-forming bacilli.

TABLE 40
Preliminary Comparison of Lime Costs for Raw, Alum, and Iron Sludges (113)

Sludge Type	Raw	Alum	$FeCl_3$
Chemical Dose to Primary (mg/l)	0	27.3 Al	20.7 Fe
Sludge Suspended Solid (g/l)	89.1	32.1	20.1
Sludge Volatile Solids (% of SS)	64.0	55.9	45.7
pH before lime	5.2	6.2	6.2
pH after lime	11.0	11.0	11.0
$Ca(OH)_2$ added, (g/l sludge)	8.7	12.9	5.5
(g/g dried solids)	0.098	0.40	0.27
Cost of lime (\$/ton dry solids)*	1.96	8.00	5.40

*Based on $Ca(OH)_2$ cost of \$20/ton. Multiply by 1.10 for \$/metric ton.

TABLE 41
Bacteriological Studies of Sludge Produced in Plant-Scale Tests (113)

	Bacterial Count (organisms/liter of sludge		
Sludge	Salmonella Species	Pseudomonas aeruginosa	Total Aerobic Count x 10^{-8}
Alum-primary	110	1300	41
Limed alum-primary	None detected	None detected	5.0
Ferric-primary	$>$ 24,000	610	190
Limed ferric-primary	None detected	None detected	0.29

The addition of lime has effectively reduced the percent volatile solids of the sludge, as is shown in Table 42. Furthermore, filterability of alum and iron sludges was improved by the addition of lime. Data obtained are presented in Table 43.

TABLE 42
Effect of Lime Addition on Dissolved Solids and Percent Volatile Solids (113)

	Dissolved Solids (g/l)		Percent Volatile Suspended Solids	
Lime Treatment	Al^{+++}	Fe^{+++}	Al^{+++}	Fe^{+++}
Before treatment	1.7	1.7	66	64
After treatment	2.1	1.7	55	60
Increase	0.4	0	-11	-4

TABLE 43

Effect of Lime on Filterability of Al^{+++} and Fe^{+++} Sludges(113)

SLUDGE PROPERTY	LIME ADDITION	Al^{+++} Dose (mg/l)			Fe^{+++} Dose (mg/l)	
		31.8	22.7	13.6	31.0	15.5
Buchner Funnel Tests						
Specific Resistance at 20" Hg ($cm/g \times 10^{-11}$)	Before	19.0	28.0	29.0	14.9	21.6
	After	3.8	4.5	3.8	7.0	5.5
Compressibility	Before	0.50	0.46	0.59	0.53	0.60
	After	0.70	0.91	0.80	0.43	0.76
Filter Leaf Tests						
Yield ($lb/hr/ft^2$)*	Before	0.98	0.94	0.95	1.06	1.57
	After	1.97	2.10	2.58	1.57	2.40
Cake Moisture (lb w/lb d.s.)	Before	4.31	4.35	4.37	4.10	3.75
	After	3.87	3.92	3.83	4.28	3.75

*Multiply by 4.86 to get $kg/hr/m^2$

Solvent Extraction

Application of solvent extraction methods known as the "McDonald Process" for treatment of wastewater sludge is discussed by Stallery (117). This process involves a number of steps, including dewatering of the sludge by centrifugation, solvent extraction with carbon tetrachloroethylene, and distillation. The resulting end products are generally fats, dried oils and grease. Although this process proved to be very efficient, it is believed to be impractical in wastewater treatment because of high expense.

Electrical Treatment

Slagle and Roberts (118) have made an extensive investigation at both laboratory and pilot plant scales of sludge treatment by electrodialysis. They found this method of sludge treatment to have advantages over chemical conditioning and other methods. To compare this method with chemical conditioning, a fresh sludge containing 6.5% solids was used. The resulting comparative data are shown in Table 44.

TABLE 44

Comparison of Chemical Treatment and Electrodialysis Treatment (118)

Chemical Treatment (per ton of dry solids)	Electrodialysis Treatment (per ton of dry solids)
89 lbs of ferric chloride used	181 KWH expended
70% filter cake moisture	59.5%
2065 lbs filter cake solids	1440 lbs
4665 lbs filter cake water	2130 lbs
6.2 pH	3-4 pH

The costs of sludge treatment using electrodialysis were found to be much more attractive than chemical conditioning of the sludge.

The electro-osmosis process has also been investigated and reported by Cooling et al (119), and Beaudoin (120). It was concluded that although the process of sludge treatment is technically very promising, it is not economically feasible.

SLUDGE CONDITIONING

Sludge is conditioned principally to improve its dewatering characteristics. Various methods of sludge conditioning are being practiced in wastewater treatment plants with the most common methods being elutriation and chemical conditioning. Other methods include: freezing of the sludge and addition of fly ash, diatomaceous earth, or other flocculating agents. The sludge moisture content can be reduced from 95 to 99% to about 70 to 75% (9) by means of proper conditioning followed by a dewatering process. One of the mechanisms of sludge conditioning using chemicals reduces the charge of the suspended particle thus decreasing the water affinity of the sludge solids and promoting particle coalescence. According to Carnes (13) conditioning can be applied at any point in the train of unit processes included in solids handling. The ideal point of application is dependent on the performance required, subsequent handling, and the characteristics of the waste solids.

Elutriation of Sludge

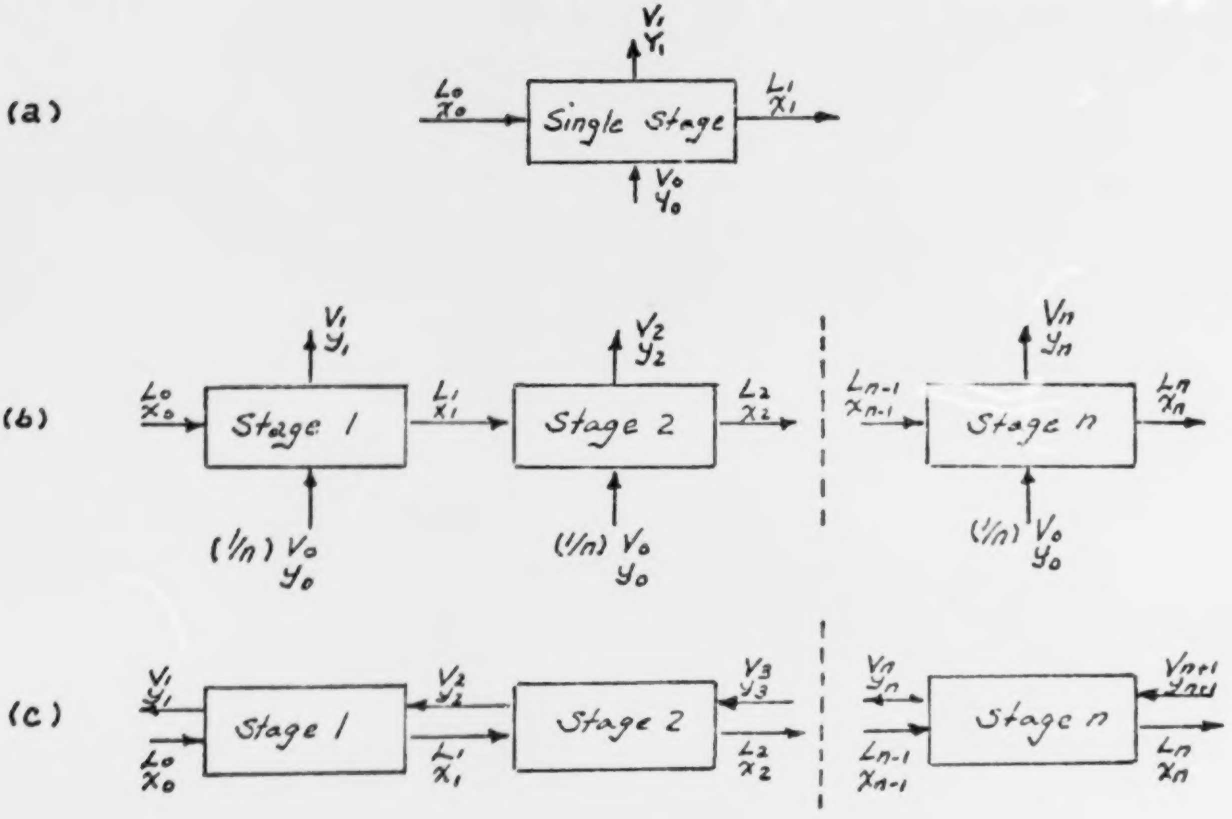
Elutriation has been defined as a washing operation which removes sludge constituents that interfere with sludge thickening and dewatering processes (17).

The elutriant used is usually settled or biologically treated wastewater. As the elutriant comes in contact with the sludge particles, dispersants such as carbonates and phosphates are extracted from the sludge as well as non-settleable fine particles and the products of decomposition. This results in a sludge of high porosity, with lower requirements for coagulant chemicals because of less surfaces to be treated and lower concentration of chemical interference (9). It has been observed that the bicarbonate alkalinity of the sludge liquor increases dramatically during the digestion process, which in turn causes a drastic increase in the chemicals required for conditioning. Thus, elutriation is applied, reducing the alkalinity and consequently lowering the chemical requirements. Other advantages of elutriation as noted by Genter (121) include the washing out of the toxic materials that inhibit sludge digestion or other biological processes, and the treating of dirty digester supernatant liquor.

Elutriation operations can be performed as a batch or continuous process. Figure 26 shows flow diagrams of the three methods of operation by Rich (66). Operation can be single stage with single contact between the solids and the liquid. It could be multistage contact in one or more basins, or it can be multistage countercurrent contact.

For determination of the alkalinity of the elutriated sludge, the following equation has commonly been used.

Figure 26
Flow Diagrams Illustrating Various Arrangements Employed in Dispersed- Contact Leaching Operations (66)
(a) Single Contact
(b) Multistage Co-current Contact
(c) Multistage Countercurrent Contact


(a)
V₁ Y₁
L₀ x₀
Single Stage
L₁ x₁
V₀ y₀
(b)
L₀ x₀
Stage 1
V₁ y₁
(1/n) V₀ y₀
L₁ x₁
Stage 2
V₂ y₂
(1/n) V₀ y₀
L₂ x₂
Lₙ₋₁ xₙ₋₁
Stage n
Vₙ yₙ
(1/n) V₀ y₀
Lₙ xₙ
(c)
V₁ y₁
L₀ x₀
Stage 1
V₂ y₂
L₁ x₁
Stage 2
V₃ y₃
L₂ x₂
Vₙ yₙ
Lₙ₋₁ xₙ₋₁
Stage n
Vₙ₊₁ yₙ₊₁
Lₙ xₙ

1. Single stage elutriation $E = \frac{D+RW}{R+1}$

2. Multistage elutriation $E = \frac{D+W\left[(R+1)^n-1\right]}{(R+1)^n}$

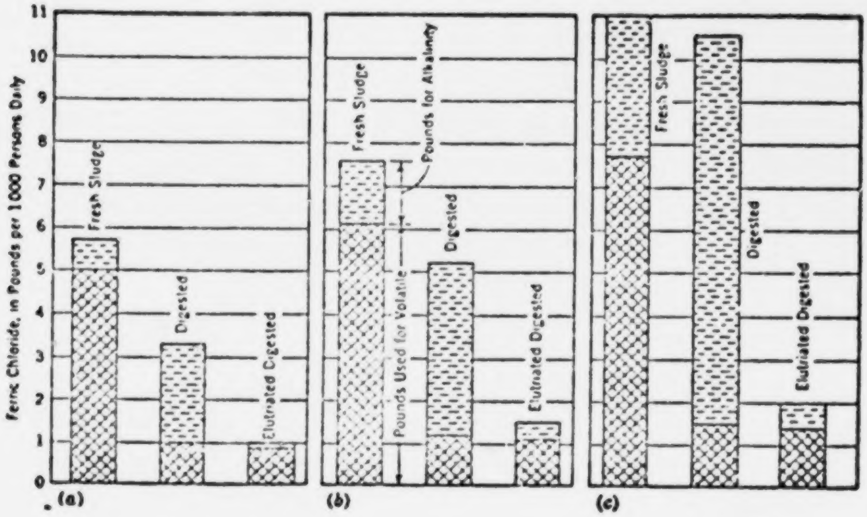
3. Multistage countercurrent elutriation $E = \frac{D+(W)(R)^{2+R}}{R^2+R+1}$

where;

D = sludge liquor alkalinity, mg/l
E = elutriated sludge alkalinity, mg/l
W = elutriated water alkalinity, mg/l
R = ratio of elutriating water to sludge alkalinity.

Elutriation of digested sludge removes the constituents that interfere with chemical flocculation. The work of Genter (123) (Figure 27) supports this fact for (a) primary sludge, (b) primary and filter humus, and (c) primary and waste-activated sludge.

Figure 27
Quantity of ferric chloride required for vacuum filtration of various domestic sludges (45)



Chemical Conditioning

Use of chemicals for the purpose of sludge conditioning results in coagulation of the solids and the release of the absorbed water from the solid particles. The literature reveals that many investigators have made extensive studies on the use of various types of chemicals for sludge conditioning. At present, the most common types of chemicals used in conditioning of wastewater sludge include: ferric chloride; ferric chloride combined with lime; ferric chloride combined with alum; or lime alone (17,124). Reviewing the sludge conditioning method of 18 plants, Zack (125) found that ferric chloride, alone, was used in plants dewatering waste activated sludge, while ferric chloride and lime were commonly used for those plants dewatering raw and/or digested sludge. Table 45 represents typical dosages used for various types of sludges. However, actual dosage for a given plant may vary considerably from these figures (14). Dosage variations depend on many factors. For example, digested sludge dewaters in a mannner varying with the duration of the digestion. Activated sludge dewatering depends on its state of oxidation (9). The chemical dosage required for a given sludge is determined in the laboratory, using a filter leaf test kit, or a modified Buchner funnel procedure (9,14).

TABLE 45

Dosage of Chemicals for Various Types of Sludges (Conditioners in Percentage of Dry Sludge)(14)

Description	Fresh solids		Digested		Elutriated digested	
	$FeCl_2$	CaO	$FeCl_2$	CaO	$FeCl_2$	CaO
Primary	1-2	6-8	1.5-3.5	6-10	2-4	---
Primary and trickling filter	2-3	6-8	1.5-3.5	6-10	2-4	---
Primary and activated	1.5-2.5	7-8	1.5-4	6-12	2-4	---
Activated (alone)	4-6					

Table 46 gives a partial listing of wastewater treatment plants using chemical conditioning, together with their dosage rates, and resulting cake yield and solids recovery. The solids recovery varied from 88 to 95%.

Polyelectrolytes

Polyelectrolytes or organic polymers have gained much popularity in recent years as a sludge conditioner. Dahl et al (126) has made extensive studies using synthetic organic polymers as sludge conditioners. Results showed that: (1) conditioning of sludge significantly improved its dewaterability, and (2) solids captured during

TABLE 46

Illustrative Data, Vacuum Filters with Lime and Ferric Chloride Conditioning(9)

Installation	Feed Sludge Dry Solids		Chemical Dosage As % Dry Feed Sludge Solids		Sludge Cake				Type of Sludge
	Solids (%)	Dry Weight (tons/day)	$FeCl_3$	CaO	Solids (%)	Volatile (%)	Yield (lb/hr/sq ft)	Dry Solids Recovery (% of total)	
Cleveland, southerly	4.0	37.0	4.5	10.7	25.2	41.6	1.84	93	elutriated, digested primary, and activated
Cleveland, westerly	8.6	4.4	2.6	12.3	34.6	45.3	3.98	94	digested primary
Cincinnati, Mill Creek	11.8	41.0	1.9	6.0	37.4	30.8	4.17	95	elutriated, digested primary
Dayton	6.4	4.8	5.6	16.1	24.4	--	3.80	88	digested primary and humus
Detroit	10.4	157.0	1.6	10.2	36.9	53.0	3.95	99	primary with 75 to 80 percent digested and 20 to 25 percent raw
Indianapolis	5.6	51.0	4.0	14.9	26.8	61.1	5.48	95	primary raw
Minneapolis-St. Paul	7.2	134.0	0.8	2.2	27.2	72.9	3.11	95	primary raw

Note: Tons × 907 = kg; lb/hr/sq ft × 4.88 = kg/hr/sq m.

the elutriation were increased from 57 to 92%. Bugg et al (127) reported on conditioning of alum sludge from water treatment plants with polymers. The results of their investigation indicated the following: (1) anionic polymers were somewhat superior to nonionic agents, and performed exceptionally well when compared with cationic chemicals, (2) cationic polymers were effective only at low pH ranges, whereas nonionic and anionic polymers were most effective at pH ranges of 6 to 10. Sharman (128) reported that the results of substituting polymers for ferric chloride included: (1) the solids content of the filter cake was increased drastically; (2) the non-combustible content of the filter cake was lowered substantially; and (3) the chemical dosage rate was lowered significantly, e.g. from 220-359 lb/ton of dry solids filtered when ferric chloride was used, to 2.5-3.6 lb/ton of dry solids filtered when organic polymer was used.

Sherbeck (134) reported on the use of synthetic organic polymers for sludge conditioning in Bay City Sewage Treatment Plant. The results of 36 months of operation, costs of inorganic conditioners and organic polymers were reported. These data are presented in Tables 47 and 48. Table 49 represents typical dosages of polymers used for sludge conditioning, the resulting cake yield, and the final solids content.

TABLE 48

Cost of Chemicals for Sludge Conditioning(134)

Substance	Cost/Ton Dry Solids ($)
Kiln-dried lime and ferric chloride	9.93
Carbide lime and ferric chloride	6.85
Polyelectrolyte C-32	14.50
Polyelectrolyte C-31	11.20
Polyelectrolyte C-149	7.00
Polyelectrolyte A-21	2.75

The application of polymers has also been discussed by other investigators, such as Dickert (129), Goodman (130,131), Burd (17), Morris (132), and Bargman (133). Reviewing these discussions and others, the following observations are made: (1) every individual polymer tested behaved differently, however, some general similarities do exist; (2) a wide variety of polymers are presently available which imposes difficulties in selecting the one that gives optimum results for a given sludge; (3) some polymers used for elutriation of digested sludge performed excellently while others required addition of ferric chloride; (4) some polymers,

TABLE 47

A Comparison between Lime, Ferric Chloride and Polyelectrolytes for Conditioning Sludge(134)

Year	Dry Solids (tons)	Solids in Sludge (%)	Yield (psf/hr)	Amount of Substance Added (lb)						Solids in Sludge (%)	Vol. in Cake (%)	Operation Time (hr)
				Lime	$FeCl_2$	C-31	C-32	C-149	A-21			
1959	461	11.2	3.1	162,000	31,000	--	--	--	--	40.1	64.1	2,125
1960	580	11.2	3.1	225,000	44,000	--	--	--	--	39.0	62.1	2,420
1961-62	424	10.9	5.3	--	--	--	5,562	--	--	35.9	75.6	1,119
1962-63	415	10.7	5.5	--	--	10,300	--	--	--	34.5	73.7	1,114
1963-64	437	10.2	6.3	--	--	--	Total of all three polymers 7,671			34.6	75.9	1,301

TABLE 49

Illustrative Data, Vacuum Filters with Polymer Conditioning$^{(9)}$

Installation	Feed Sludge Dry Solids		Chemical Dosage As % Dry Feed Sludge Solids		Sludge Cake				Type of Sludge
	Solids (%)	Dry Weight (tons/day)	Polymer (cationic)	Polymer (anionic)	Solids (%)	Volatile (%)	Yield (lb/hr/sq ft)	Dry Solids Recovery (% of total)	
Atlanta, S. River(53)	8.0	11.34	0.95		23.0	--	6.7	--	elutriated, digested primary, and activated
Erie, Pa. (91)	6.2	10.65	1.4		--	--	2.5	--	digested primary and activated
Erie, Pa. (91)	5.3	16.55	1.56*		--	--	2.5	--	elutriated, digested primary, and activated
Hamilton, Ontario (92)	--	--	0.14 Polymer $FeCl_3$ (cationic)		29.5	--	8.9	--	digested primary
Ann Arbor, Mich. (42)	2.0	7.02	0.72	12.0	20.0	--	--	--	elutriated, digested primary, and activated
Battle Creek, Mich. (42)	5.5	21.64	0.89	0.93	23.5	--	--	--	digested primary and humus (3/4) + raw (1/4)
Battle Creek, Mich. (42)	4.5	19.76	0.72	4.47	20.0	--	--	--	digested primary and humus

*0.075- to 0.125-percent anionic polymer used in elutriation prior to conditioning and filtration.

Note: Tons × 907 = kg ; lb/hr/sq ft × 4.88 = kg/hr/sq m.

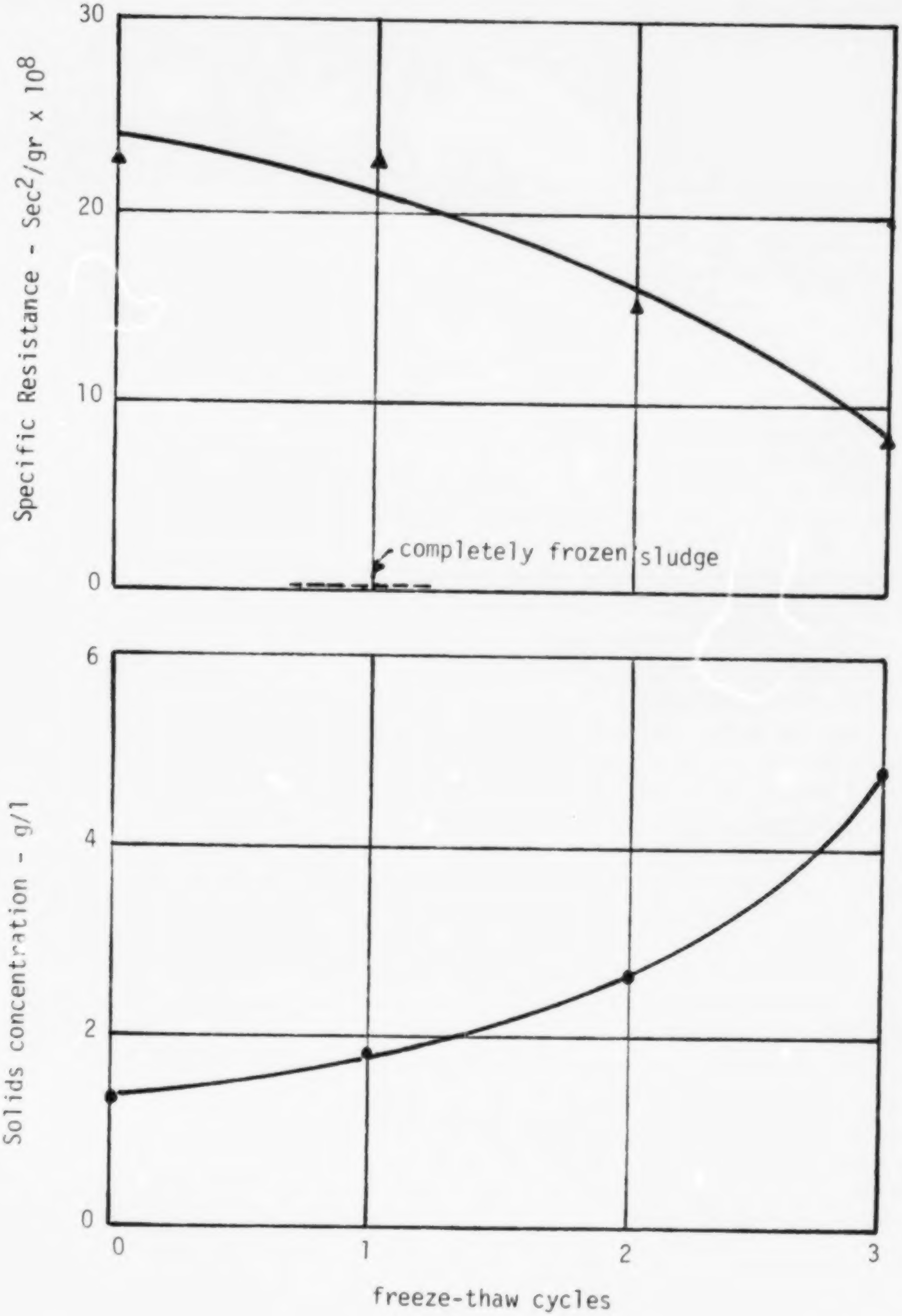
while performing as an excellent coagulant agent as in the elutriation process, did not improve dewaterability of sludge; (5) polymers used to condition sludge for subsequent dewatering, in general, showed little improvement in the settling rate; and (6) predictions as to the action of a particular polymer on a particular sludge seem to have little validity with the most practical approach to the problem being a trial and error procedure.

Freezing

Katz and Mason (135) have reported on the application of a freezing method for conditioning activated sludge prior to dewatering. Results of their comprehensive investigation were as follows: (1) solids production rate was found to be significantly high, on the order of 50 lb/sq-ft/hr; (2) quality of filtrate and filter cake produced from freeze-conditioning was equivalent or better than from conventional vacuum filter operation; (3) gravity draining using wire screen cloth (40-80 mesh) satisfactorily dewatered freeze-conditioned sludge; and (4) the conditioning effect produced by freezing was believed to be a result of dehydration and the pressure exerted on the sludge particles by the ice structure.

Farrell and co-workers (136) have made a comprehensive study of the application of natural freezing for dewatering of aluminum hydroxide sludge. According to Farrell "aluminum hydroxide sludges, when frozen slowly and completely, change structure character completely upon thawing. A rapidly, settleable, high density precipitate is obtained." Conclusions of the study made were: (1) distinct similarity between freezing rate of sludge to that of water was observed with the sludge freezing rate being about 10% slower because the natural convection is reduced during the stage when the liquid is being cooled to the freezing point; (2) snow cover was believed to be detrimental to freezing of sludge, even in extremely cold climates;(3) significant increase in solids content and dewaterability of the sludge is attainable by slow freezing and thawing, provided that the freezing is complete as shown in Figure 28; (4) freezing can be used in mild climates only if sludge is applied in thin layers of 0.5 to 1.0 inch thickness; and (5) presence of phosphate from 0 to 1 mole phosphorus per mole of aluminum did not change filterability and solids content of the frozen sludge significantly, as shown in Table 50. Conditioning of sludge by freezing has been investigated. Results of these investigations are summarized as follows: (1) freezing is applicable to all types of sludge; (2) addition of flocculant agent enhanced conditioning of sludge but is not required; (3) good dewatering results can be

Figure 28
Effect of Repeated Partial Freezing on Sludge Properties(136)



obtained if freezing is slow and complete; (4) increasing the freezing period did not affect dewaterability; (5) thawing of sludge can be done in any manner, provided that it is not accompanied by vigorous agitation; and (6) freezing increased the rate of settling.

TABLE 50
Effect of Freeze-Thaw Cycle on Properties of Aluminum Hydroxide Sludges with Varying Amounts of Phosphate (136)

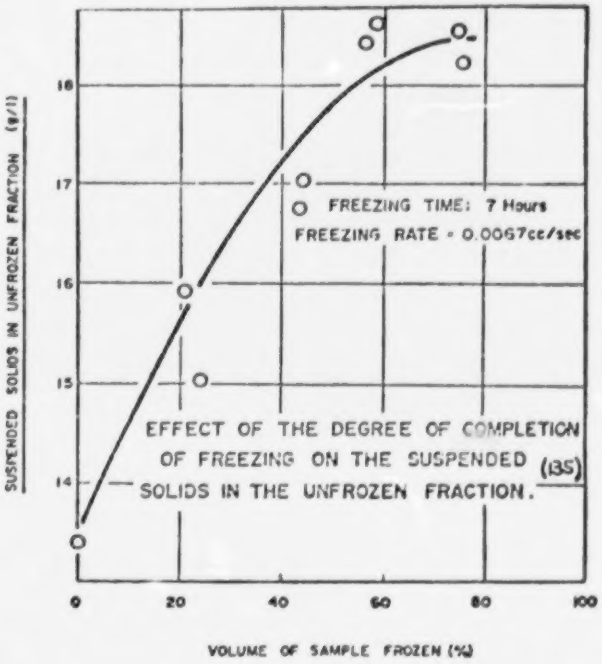
Nominal P/Al Molar Ratio	Before Freezing		After Freezing	
	Solids Content g/l	Specific Resistance sec^2/g x 10^8	Solids Content g/l	Specific Resistance sec^2/g x 10^8
0	3.20	10	176	0.04
0.34	2.50	19	168	0.06
0.69	3.20	16	180	0.06
1.04	2.84	16	178	0.07

Theoretically, if water containing impurities is frozen at a slow rate, the impurities are rejected from the ice structure and become concentrated in the liquid fraction (137). The freezing rate for the rejection of impurities is about 0.0005 cc/sec, and when the rate exceeds 0.001 cc/sec, impurities will be captured in the ice crystals. The freezing rate used in sludge is about 0.0067 cc/sec, (137) resulting in the capture of some solids in the ice structure. The effect of freezing on the concentration of suspended solids in the unfrozen fraction of the sludge was demonstrated, (135) as shown in Figure 29. The effect of extent of freezing on the dissolved solids in the unfrozen fraction of sludge is shown in Figure 30.

Fly Ash Conditioning of Sludges

Use of fly ash to condition the sludge from wastewater treatment plants, for subsequent dewatering, has recently been investigated by a number of investigators. Eye and Basu (138) made an extensive study on the effect of fly ash in improving filterability of digested sludge. A summary of their results is as follows: (1) it was found that a 1:1 mixture of fly ash to sludge filtered better than digested sludge alone; (2) addition of chemical conditioning to this mixture increased filterability significantly, as shown in Table 51; (3) and optimum filtering condition (minimum filtering time) was obtained when sludge-fly ash ratios ranged from 3:1 to 4:1, as shown in Figure 31.

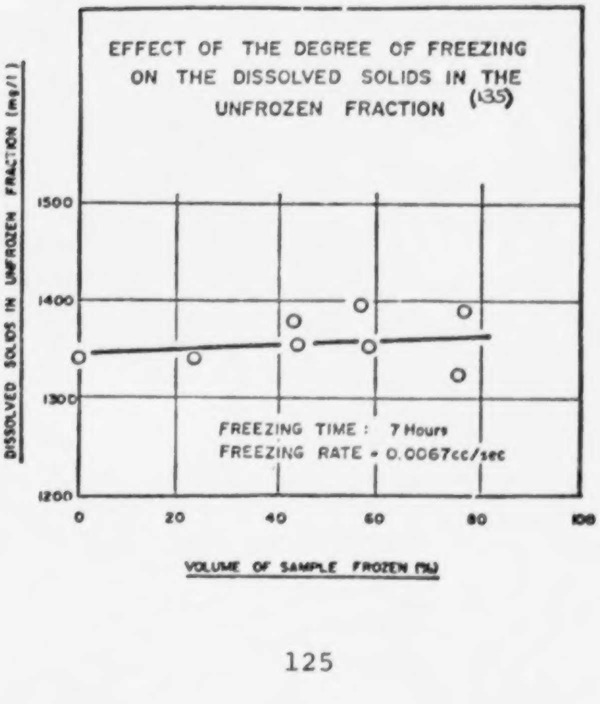
Figure 29



FREEZING TIME: 7 Hours
FREEZING RATE = 0.0067cc/sec

EFFECT OF THE DEGREE OF COMPLETION OF FREEZING ON THE SUSPENDED SOLIDS IN THE UNFROZEN FRACTION. (135)

Figure 30



EFFECT OF THE DEGREE OF FREEZING ON THE DISSOLVED SOLIDS IN THE UNFROZEN FRACTION (135)

FREEZING TIME: 7 Hours
FREEZING RATE = 0.0067cc/sec

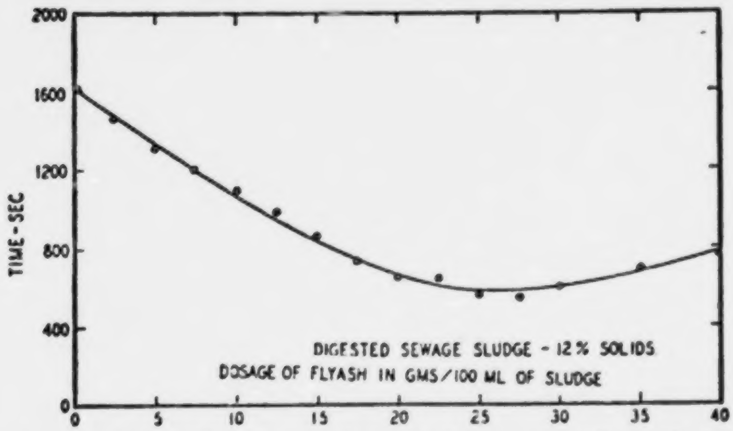
TABLE 51

Typical Sludge Filterability by Buchner Funnel Test
(Secondary Effluent at Vacuum of 15 in. Hg. Sample Volume = 50 ml)[138]

Flyash Sludge 22% Solids by Weight		Digested Sludge (No Chemicals) 13% Solids by Weight		Flyash Sludge & Digested Sludge 1:1		Digested Sludge with Chemicals		Flyash Sludge & Digested Sludge 1:1 with Chemicals		Solids Content in Cake (% by Weight)
Time (sec)	Filtrate Vol (ml)	Time (sec)	Filtrate Vol (ml)	Time (sec)	Filtrate Vol (ml)	Time (sec)	Filtrate Vol (ml)	Time (sec)	Filtrate Vol (ml)	
10	12	25	3	10	3	10	12	10	16	Only flyash sludge = 65%
15	16	35	4.5	15	4	15	22	15	24	
20	23	60	7	20	5.0	20	28	20	27	
25	27	100	10	40	8.5	25	31	25	30	Only digested sludge with chemicals = 52%
30	31.5	190	15	60	12.0	30	32.5	30	31.5	
35	34.0	230	17	80	14.5	35	34.0	35	32.5	
40	35.0	335	21	100	16.5	40	35.5	40	33.5	1:1 mixture without chemicals = 56%
45	35.5	555	28	145	22.0	50	36.5	50	34.5	
50	36.0	630	30	200	28.0	70	37.0	85	35.5	
60	36.2	730	32	250	32.0	100	37.0	110	35.8	1:1 mixture with chemicals = 59%
80	36.5	945	35	300	35.0					
100	36.8	1190	37	360	37.0					
120	37.0	1410	38	400	37.5					
		2200	39.2							

Figure 31

Flyash dosage vs. time to collect 50 ml of filtrate. (138)



Tanney and Cole (139) investigated the use of fly ash for conditioning of activated and digested sludge. Results showed that the amounts of fly ash required for improving filterability of activated sludge ranged from 500 to 700 percent of the initial solids content of the sludge, whereas for digested sludge they ranged from 100 to 150 percent.

Malina (111) in discussing the Beloit-Passavant "SLUDGE ALL" process has indicated that fly ash has been used as the conditioner agent with the ratio of fly ash-solid ranging from 1:1 to 4:1 on dry-weight basis, depending on the type of sludge used. He further noted that one advantage of adding fly ash as a conditioning agent is that the fine fly ash particles have the capability of trapping many of the particles present in the sludge. Table 52 presents typical pilot-plant operation data obtained using fly ash as the sole conditioning agent.

TABLE 52

Operating Data: Beloit-Passavant "SLUDGE ALL" System (111)

	Sludge			Filter Cake	
Type of Sludge	Suspended Solids (Percent)	Volatile Solids (Percent)	Ash-Sludge (Ratio)	Solids (Percent)	Volatile (Percent)
Raw + activated	4.90	66.5	1:1	40.0	29.0
Raw + activated	4.10	69.0	3.1	55.0	23.0
Activated	0.90	77.0	3:1	29.0	29.0
Activated	0.98	69.0	2:1*	40.0	27.0
Digested	6.20	50.0	2:1	52.2	17.4
Digested	6.36	47.5	3:1	59.4	18.4
Waste activated	1.20	71.0	2:1	58.2	29.0
Waste activated	1.00	64.0	3:1	62.1	26.9

*15% lime.

Filter Aids

It has been observed that the specific resistance of certain sludges can be reduced by adding fibrous or particulate material. These added materials together with the solid particles of the sludge form a porous, permeable, and rigid lattice structure which filters particulates but allows passage of liquid. These materials are particularly effective for sludge structures that are highly compressible and tend to blind or slime the filtration medium (9). Filter aids include diatomaceous earth, sawdust, news prints, pulped magazine paper, wood chips, etc.

Malina (111) reported the results of laboratory-scale investigation of the use of filter aids as well as organic and inorganic polymers. Results shown in Figures 32, 33, and 34 indicated that newsprints as well as pulped magazine paper could be used very effectively as conditioning agents.

SLUDGE DEWATERING

Sludge is the most important by-product of the wastewater treatment plant. Disposal of these materials is a problem comparable in magnitude and importance to that of treating the wastewater. Any reduction in volume of these by-products would be a significant step in improving and solving the disposal problem. Reduction of the volume of the sludge, by removal of water,has been a difficult problem since the very first days of wastewater treatment. For many years sludge dewatering was done by land methods, i.e., lagooning, and sand beds. However, recently attention has been focused on use of other techniques for sludge dewatering. Increased land costs, along with stringent land, air, and water pollution standards have made sludge dewatering an economically attractive process since it significantly reduces the volume to be disposed of and may retard biological decomposition.

The methods commonly used for sludge dewatering to be discussed briefly in this paper include:

1. Sand Bed Drying
2. Centrifugation
3. Vacuum Filtration
4. Filter Press
5. Vibration
6. Heat Drying

Figure 32

Effect of Conditioners on Specific Resistance of Activated Sludge.(111)

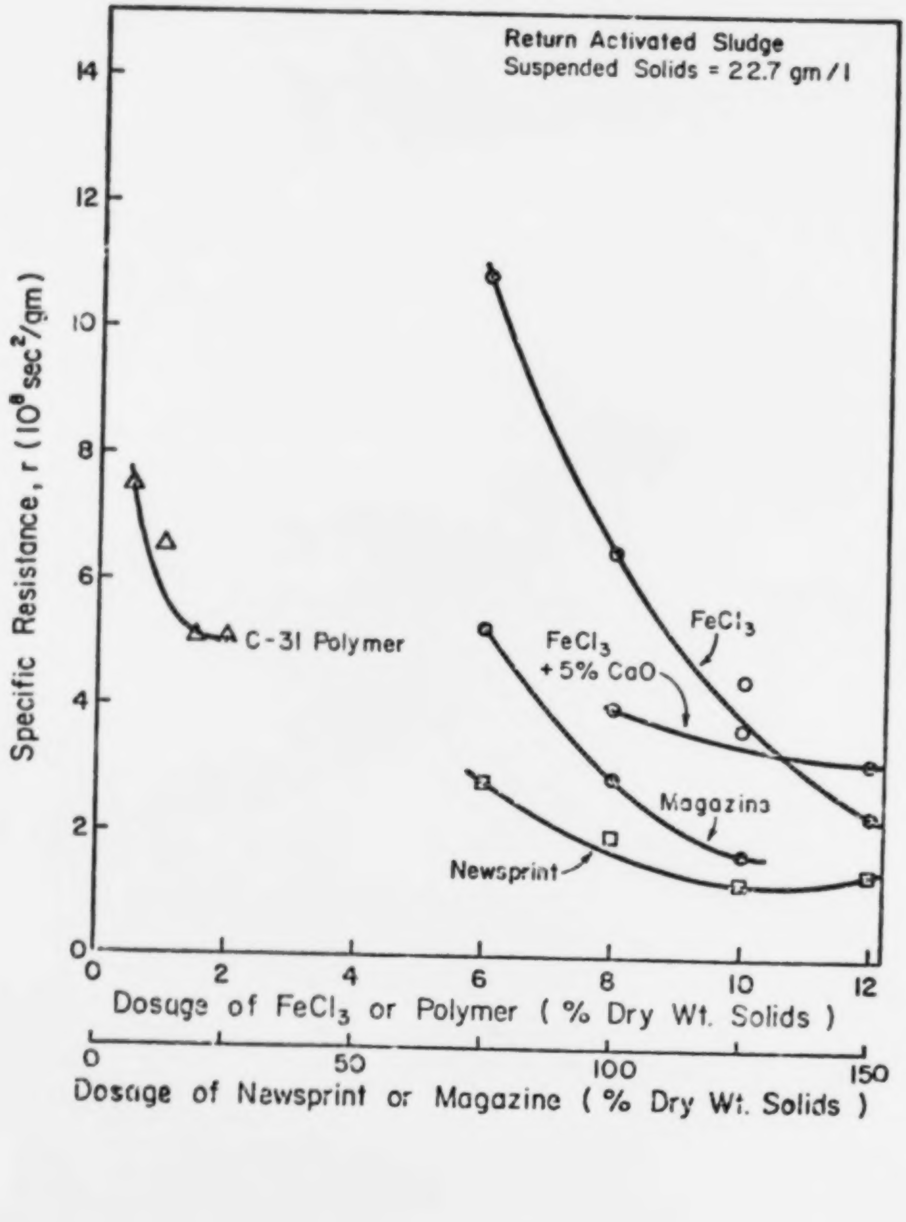


Figure 33

Effect of Conditioners on Specific Resistance of Digested Primary Sludge and Humus.(111)

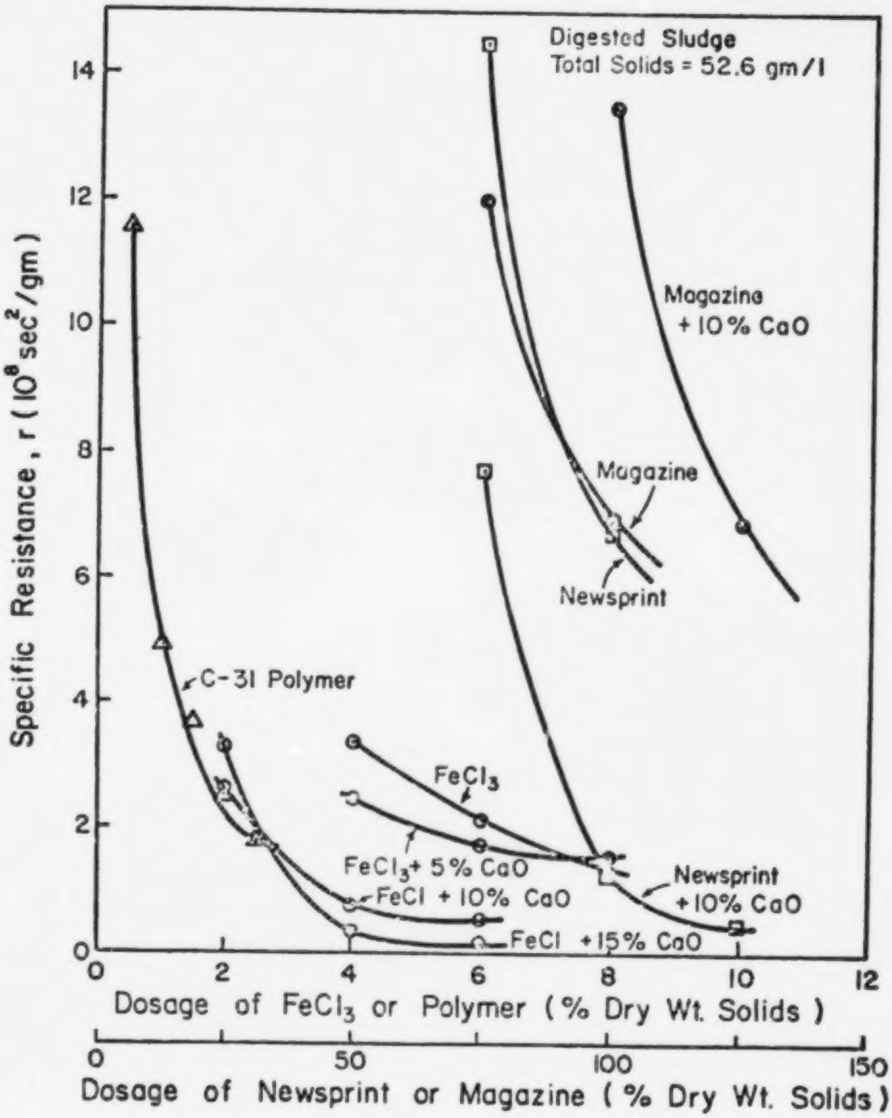
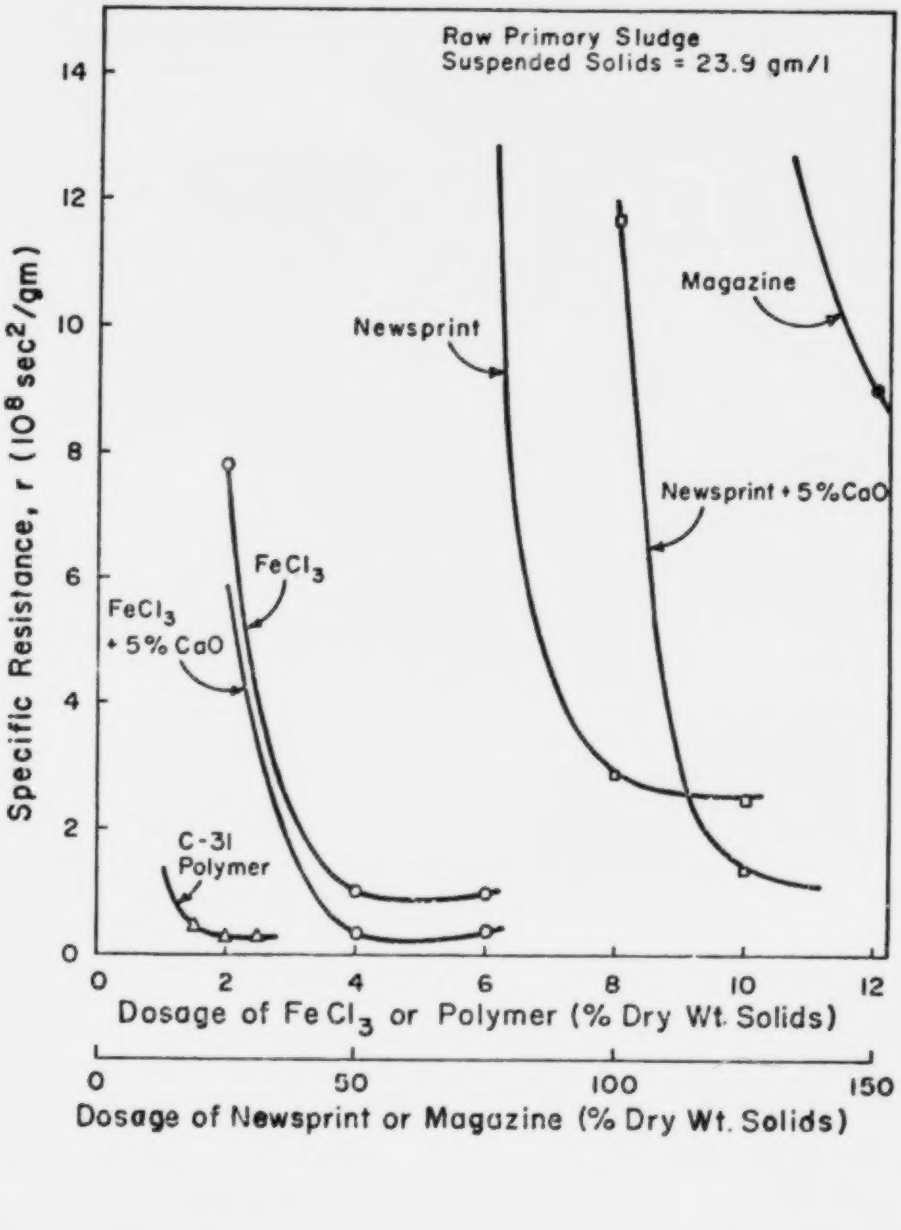


Figure 34

Effect of Conditioners on Specific Resistance of Primary Sludge.(111)



Sand Bed Drying

Drying of sludge on open or covered sand beds is perhaps the oldest and yet the most common method used to reduce the water content of the wastewater sludge to a forkable condition prior to final disposal. It is the most economical method of sludge disposal, particularly for municipal wastewater treatment plants serving small and medium size communities. Thoman and Jenkins (140) in their report on the "Statistical Summary of Sewage Works in the U.S. in 1957" stated that "over 71% of the nation's 7518 municipal wastewater treatment plants used drying beds for sludge dewatering purposes." A 1969 survey report from 27 State Health Departments (9) showed that the percentage given previously was down, as shown in Table 53. Lack of land availability, high costs of land and labor were believed to be the main reasons.

TABLE 53

1967 Report from 27 State Health Departments, Number of Sludge Drying Beds$^{(9)}$

Population of Cities	Number	With Sludge Beds %*	%+
Less than 5,000	1,886	67	73
5,000 to 25,000	750	27	22
More than 25,000	168	6	5
Total	2,804	100	100

* Percent of reported totals for 1967 survey.
+ Percent of reported totals for 1957 survey.
Note: Only 6 states reported having covered beds; 14 states reported they will continue with sludge beds in new plants; 13 states reported the use of beds with paved surfaces in lieu of sand.

Both open and closed drying beds have been used with the former being more common.

According to Jennett and Harris (141) the variables affecting the drying rate of sludge on open beds include: (1) climate and atmospheric variations, (2) sludge depth application, (3) sludge moisture content, (4) types and origin of sludge, (5) sludge age, (6) drying beds construction, and (7) presence or absence of coagulants.

The two major dewatering mechanisms influencing sludge dewatering rates on drying beds, are evaporation and drainage (9,17,141, 142). Quon and Tamblyn (143) have reported that an inverse relationship exists between the two, and that maximization of either mechanism will retard the other one. Other investigators (141, 144) have supported this theory to some extent and have pointed out that drainage is indeed the major and more significant factor.

Swanwick (145) reported that 85% of the water lost from secondary sludge was by drainage. Templeton (146) found that drainage accounted for 21% by weight of the sludge applied without use of chemicals, and Volger and Rudolfe (147) have reported that 60% of the sludge water is free or drainable. Drainage is influenced by many factors, such as : initial solids content of the sludge (142, 148); depth of supporting media (149); sand grain size distribution (149); and presence or absence of coagulants (144, 149).

Nebicker (150) reported that sludge moisture loss due to evaporation could be approximated to the removal rate from a free water surface, provided that there is free sludge surface moisture. He also noted that sludge evaporation rates would be modified by the darker sludge surface which would absorb more radiant energy and thus increase moisture loss. The evaporative rate would be decreased because of dissolved solids, and oils and fats on the supernatant surface. He also indicated that the drainage of water from the applied sludge is almost completed within three days after application of the sludge and further dewatering is caused by evaporation.

Evaporation dewatering of sludge occurs in two distinct phases: constant rate drying, and decreased rate drying. In the first phase evaporation continues until the free surface moisture is exhausted and no longer can be replenished by the internal transport of water to the sludge surface. Evaporation in the second phase proceeds at a decreasing rate, depending on the nature and characteristics of the dewatering material. It may or may not have a linear relationship with time (122).

Rate of evaporation is affected generally by factors such as air temperature, amount of sunshine, relative humidity and wind velocity. Laboratory and field investigation of these factors have been reported by numerous investigators (17, 141, 144).

In general, drainage is the predominant dewatering mechanism during the first 2 to 3 days after the application of the sludge on drying beds. After 2 to 3 days, evaporation becomes the major factor and in the course of a few days the sludge cake shrinks horizontally, and produces cracks at the surface which accelerate evaporation by exposing additional sludge surface area (151).

Effect of the dosing depth and solids content of the applied sludge on the drying time was studied by Downes. A summary of results reported by Jennett (141) is presented in Table 54.

TABLE 54
Days Required to Dry Different Depths of Sludge of Varying Solid Contents (148)

Percent Solids	Dosing Depth, inch. 8	9	10
	Drying Time, Days		
4	5.5	6.0	6.0
5	6.5	8.5	10.0
6	9.0	12.0	13.0
7	12.0	14.0	16.0
8	14.0	18.0	23.0

Haseltine (148) found that the optimum depths for the open and covered beds were 8 and 14 inches respectively. Quon and Johnson (142) reported that 8" depth for open bed gave the greatest drainage volume. The effect of polymers on dewatering rate was investigated by Jennett and Santry (144). It was found that in general, polymers were effective in increasing dewatering rate. It was also noted that greater amounts (200 mg/l dosages) of polymer did not increase dewatering rate significantly more than smaller amounts of 50 mg/l or less.

A comprehensive investigation of the effect of air temperature and relative humidity on the dewatering of anaerobically digested activated sludge was made by Jennett and Harris (141). They have reported that sludge dewatering on drying beds is not a function of relative humidity, as had been originally assumed. Also, it is shown in Figure 35 that a definite relationship exists between sludge moisture content, evaporation rate from a free water surface, and the parameters ΔT (the difference between wet and dry bulb temperature), and ΔH (the difference between saturation and absolute humidity). Data showing these relationships are presented in Table 55 and shown graphically in Figure 36. The moisture gradient (moisture content of the top layer minus the moisture content of the bottom layer) developed within the dewatering sludge generally increased with time and ΔT, as shown graphically in Figure 37. An inverse relationship was noted between drainage and evaporation; and also wind significantly affected the removal of sludge moisture with time. Total drainage and evaporation losses are summarized in Table 56.

Figure 35

(141)

Moisture Content Versus Time for Runs 1, 2, and 3

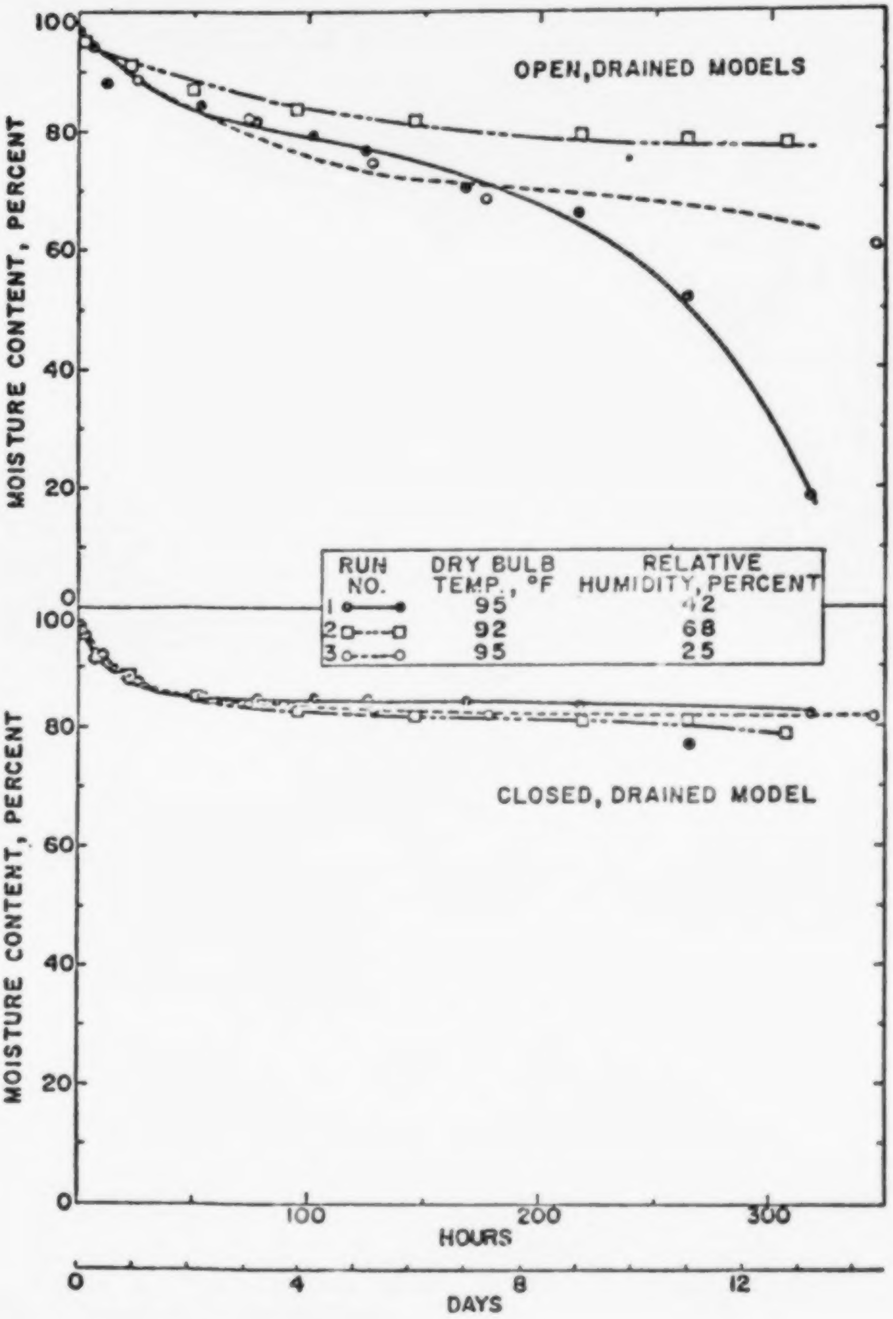


TABLE 55*

Runs 1, 4, 5, 6, 7, and 8 Ranked on the Basis of Environmental Conditions and Applicable Results(141)

Temperature			Humidity				Moisture, %		Evaporation			Drainage	
Dry Bulb ↑ (1)	Wet Bulb ↑ (2)	ΔT ↑ (3)	Rel. ↓ (4)	Abs. ↓ (5)	Sat. ↓ (6)	ΔH ↑ (7)	Init. ↓ (8)	Final ↓ (9)	Sludge ↑ (10)	Water ↑ (11)	Ratio ↑ (12)	Total ↓ (13)	% Applied ↓ (14)
1	1	1	7	4	4	1	6	1	1	1	1	4	4
7	6	7	4	5	5	7	7	7	7	7	7	8	8
6, 8	8	8	1	7	7	8	5	8	8	8	5	7	7
8, 6	7	4	8	8	8	4	1	4	6	4	6	1	1
4	5	6	5, 6	6	6	6	4	6	4	6	8	6	6
5	4	5	6, 5	1	1	5	6	5	5	5	4	5	5

*↓ - Indicates increasing order of magnitude.
↑ - Indicates decreasing order of magnitude.

Figure 36

Moisture Content Versus Time for Runs 1, 4, 5, 6, 7, and 8.(141)

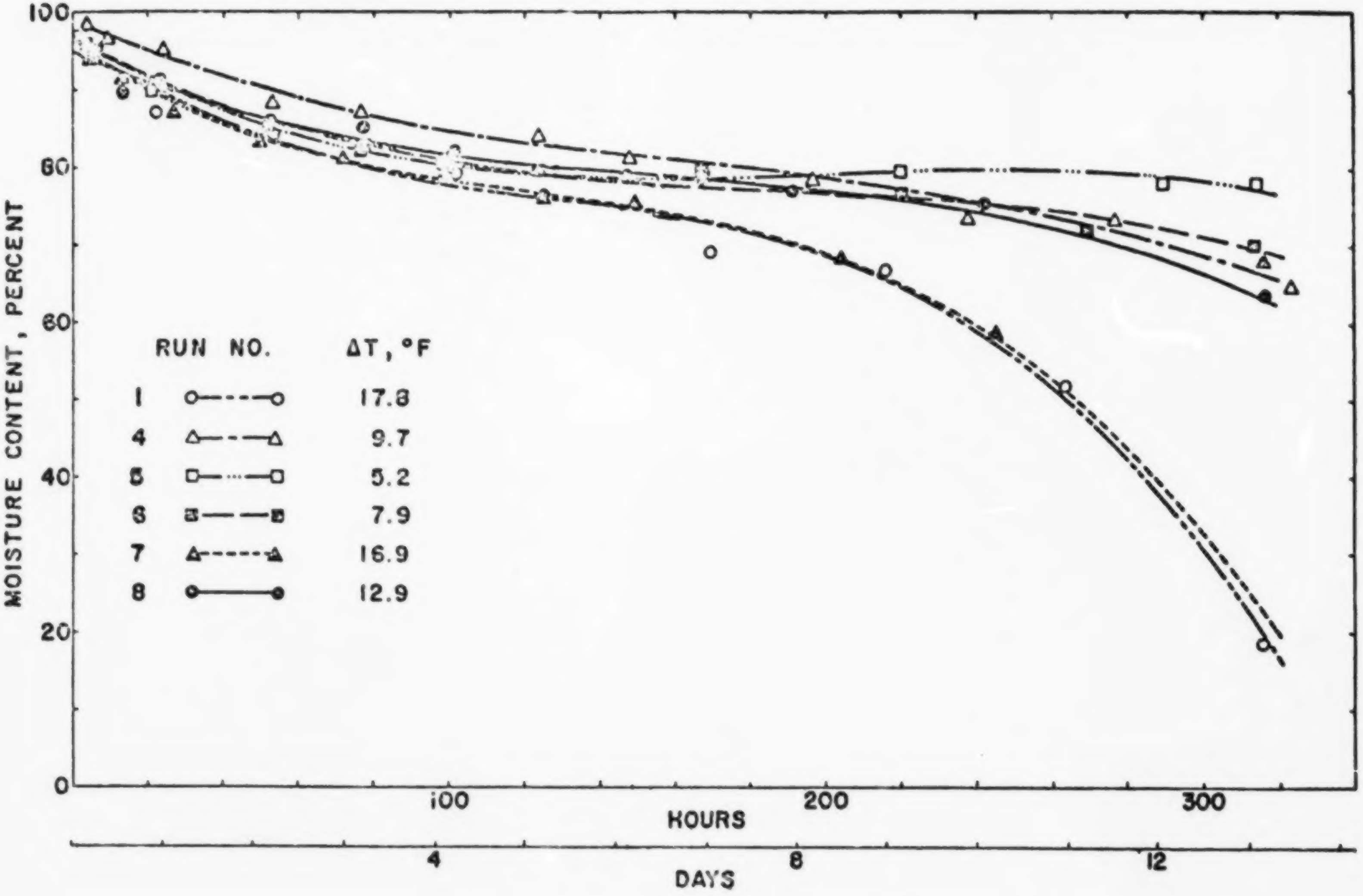


Figure 37

Moisture Gradient Versus Time for Runs 1, 4, 5, 6, 7, and 8.[141]

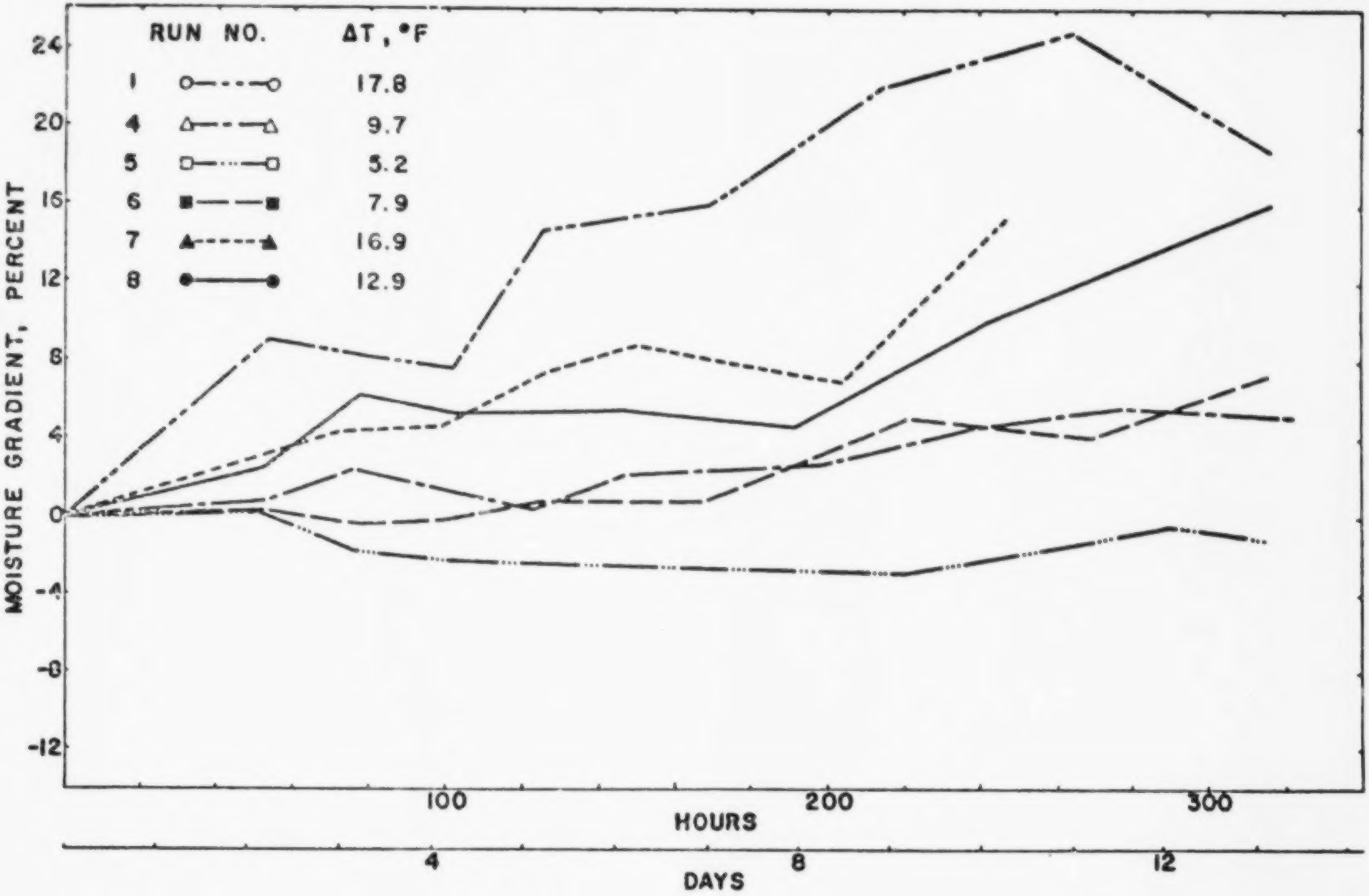


TABLE 56

Total Moisture Losses from the Open, Drained Models(141)

Run No.	Average Applied Weight of Sludge psf*	Initial Moisture Content %	Initial Water Content psf*	Drainage		Evaporation		Dewatering	
				Total psf*	% of Initial Water Content	Total psf*	% of Initial Water Content	Drainage + Evap. psf*	% of Initial Water Content
1	42.5	96.6	41.0	31.0	75.6	10.2	24.9	41.2	100.4
2	41.3	97.6	40.4	31.9	79.0	2.9	7.2	34.8	86.2
3	42.6	97.1	41.4	33.4	81.0	5.5	13.3	38.9	94.0
4	42.3	96.8	41.0	24.4	59.5	9.5	23.2	33.9	82.7
5	44.0	96.5	42.5	39.5	93.0	0.3	0.7	39.8	93.7
6	43.5	97.2	42.3	34.5	81.5	4.8	11.4	39.3	93.0
7	43.1	96.3	41.5	30.6	73.7	8.2	19.8	38.8	93.5
8	42.8	95.6	41.0	28.3	69.0	7.8	19.0	36.1	88.0

*Multiply by 4.88 to convert psf to kg/sq m.

In summary, dewatering characteristics of the sludge are dictated by many factors, such as the wastewater characteristics, type of sludge, and the efficiency and characteristics of the wastewater treatment process. Raw sludge generally contains a high percentage of fibrous and greasy materials, resulting in a bed of dense dewatered sludge cake containing only a few large surface cracks. On the other hand, beds of digested sludge contain many small cracks which allow more surface exposure to the drying air and thus greater drainage of water (9). Sludges containing grits dry faster, where sludge containing grease dries more slowly. Fresh sludge has a tendency to dry faster than aged sludge; primary sludge drains faster than secondary sludge; and digested sludge dries faster than fresh sludge (17).

For the sake of brevity, design criteria of drying beds will not be discussed here, however, some data are provided in Table 57 and Table 58.

Centrifugation

Centrifugation of wastewater sludge is a mechanical means of dewatering. The application of centrifugal force for dewatering of wastewater solids has been recognized by engineers, however, it was not until a decade ago that centrifugation gained popularity in wastewater treatment systems. Reports indicate that during the years 1967 and 968, a total of 233 installations of centrifugal dewatering units, for processing municipal and industrial sludge were made in the U.S. (9).

Centrifuges that have been used for sludge dewatering include (1) basket-design centrifuge, (2) disk design centrifuge, and (3) solid bowl conveyor centrifuge. The basket-design centrifuge did not gain popularity because liquid clarification was generally poor, although it provided a well dewatered cake. The disc-type centrifuge was effective in clarification, but operational problems and their dewatering capabilities caused their abandonment. The solid bowl conveyor centrifuge solves the problems by combining the good dewatering of one unit with the effective clarification of the other unit. A schematic of this type of centrifuge is shown in Figure 38.

Alberton and Guidi (152) have pointed out that the greatest advantage of centrifugation is its flexibility. It may be modified to meet specific process needs; or, in some cases, the process conditions themselves may be modified to improve the performance of the dewatering unit. Parameters that are affecting the efficiency of the unit include machine variables and process variables listed in Table 59.

TABLE 57

Sludge Drying Bed Area Needed for Dewatering Digested Sludge(9)

Type of Wastewater Treatment	Area (sq ft/cap)*	
	Open Beds	Covered Beds
Primary	1.00	0.75
Trickling Filters	1.50	1.25
Activated Sludge	1.75	1.35
Chemical Coagulation	2.00	1.50

*"South of 40 degrees north latitudes, these figures can be reduced 25 percent; and north of 45 degrees north latitude, they should be increased 25 percent." (2)
Note: Sq ft x 0.0929 = sq m.

TABLE 58

Sludge Drying Bed Area Needed for Dewatering Digested Sludge(9)

Type of Sludge	Area (sq ft/cap)*	
	Open Beds	Covered Beds
Primary digested	1.0 to 1.5	0.75 to 1.0
Primary and humus digested	1.25 to 1.75	1.0 to 1.25
Primary and activated digested	1.75 to 2.5	1.25 to 1.5
Primary and chemically precipitated digested	2.0 to 2.25	1.25 to 1.5

*"With glass covered beds, a greater number of sludge drawings per year is obtained because of protection against rain and snow -- actually a combination of open and enclosed beds provides maximum usage....open beds may evaporate cake moisture faster than covered beds under favorable weather conditions." (1)
Note: Sq ft x 0.0929 = sq m.

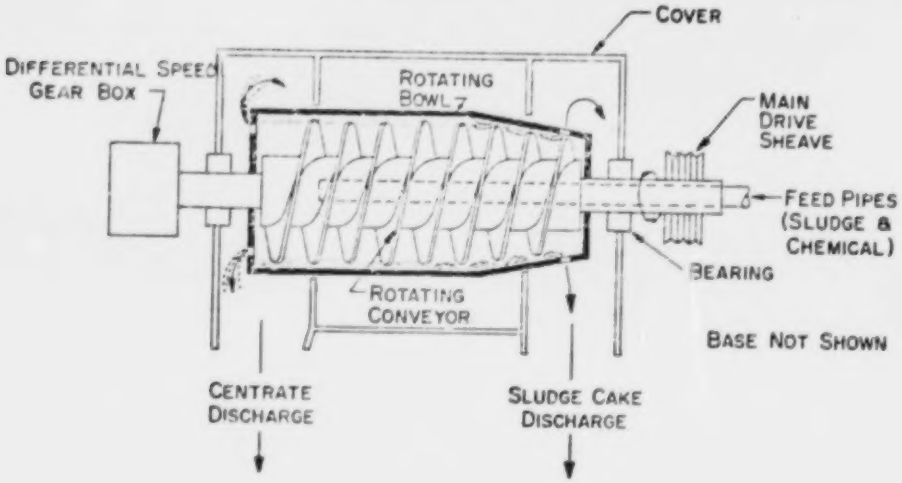
TABLE 59

Machine and Process Variables[152]

Machine Variables	Process Variables
1. Bowl Design	1. Feed Rate
a. Length-to-diameter ratio	2. Solids Characteristics
b. Bowl Angle	a. Particle Size
2. Bowl Speed	b. Density
3. Pool Volume (depth)	3. Feed Consistency
4. Conveyor Speed and Pitch	4. Temperature
	5. Chemical Aids

Figure 38

The solid bowl-conveyor sludge dewatering centrifuge assembly consists of a rotating unit comprising a bowl and conveyor.
(Courtesy Bird Machine Co.)


COVER
DIFFERENTIAL SPEED GEAR BOX
ROTATING BOWL
MAIN DRIVE SHEAVE
FEED PIPES (SLUDGE & CHEMICAL)
BEARING
ROTATING CONVEYOR
BASE NOT SHOWN
CENTRATE DISCHARGE
SLUDGE CAKE DISCHARGE

Burd (17) reported that according to Guidi, the two major factors determining the success or failure of a centrifuge are solids recovery and cake dryness. These two factors are affected by the parameters given previously in the following manner:

To Increase Cake Dryness	To Increase Solids Recovery
1. Increase bowl speed	1. Increase bowl speed
2. Decrease pool volume	2. Increase pool volume
3. Decrease conveyor speed	3. Decrease conveyor speed
4. Increase feed rate	4. Decrease feed rate
5. Decrease feed consistency	5. Increase feed consistency
6. Increase temperature	6. Increase temperature
7. Do not use flocculants	7. Use flocculants

Results of the investigations of Alberton and Guidi (152) concerning the above parameters are as follows. The effect of bowl speed on the feed rate and solids recovery is shown in Figure 39. Data indicates that a higher percentage recovery is possible for the same feed when bowl speed is increased. Furthermore, if bowl speed is increased about 40%, feed rate would be double while the same solids recovery is achieved.

The effect of pool depth is shown in Figure 40. It is obvious that the deeper pool produces higher solids recovery, whereas the medium pool gives lower solids recovery, but higher cake solids.

Figure 41 shows the effect of feed rate on solids recovery for two types of sludges; whereas,Figure 42 indicates a typical relationship exists between the two factors.

Chemical conditioning of the sludge prior to centrifugation has been found to improve solids recovery dramatically. Alberton and Sherwood (153) investigated the use of polymer for enhancing and dewatering of various types of sludges. A summary of their results is: (1) in case of digested primary sludge, there is no need for polymer conditioning if the unit is hydraulically loaded within its clarification capacity, however, if polymers are used to enhance clarification, machine capacity will be greatly increased; (2) in the case of a combination of digested primary and biofilter sludge, polymer conditioning increased solids recovery to only 85% at a feed rate of 1 to 2 gpm, using a short-bowl unit; and (3) in the case of digested primary mixed with activated sludge, polymer conditioning increased solids recovery from 75% to 96% of the feed solids, but the cake solids decreased from 23% to 20.5% as shown in Figure 43.

Figure 39

Effect of Bowl Speed on Recovery(152)

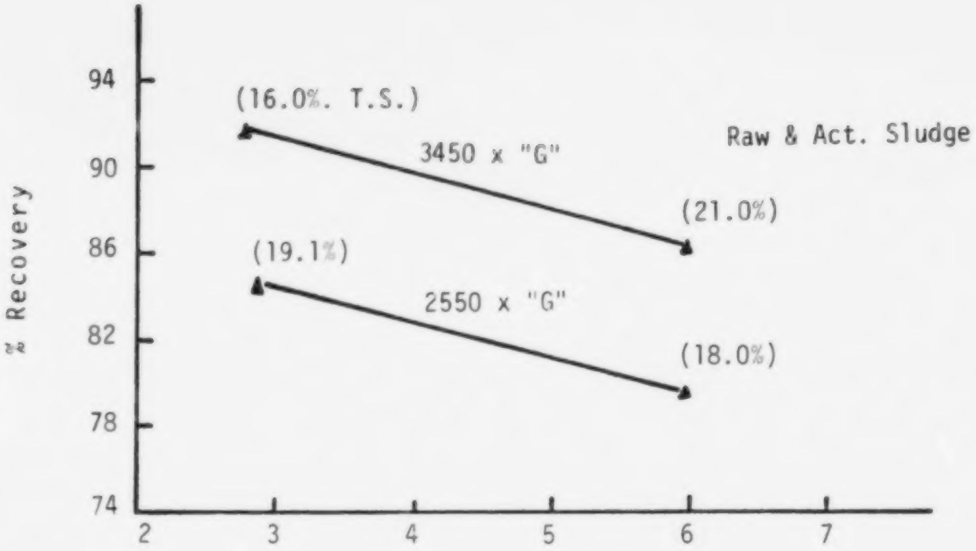


Figure 40

Effect of Pool Depth on Percent Recovery(152)

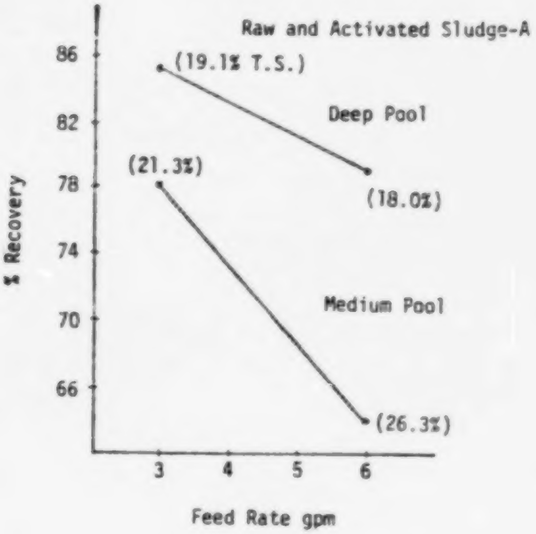


Figure 41

Effect of Feed Rate on Percent Recovery(152)

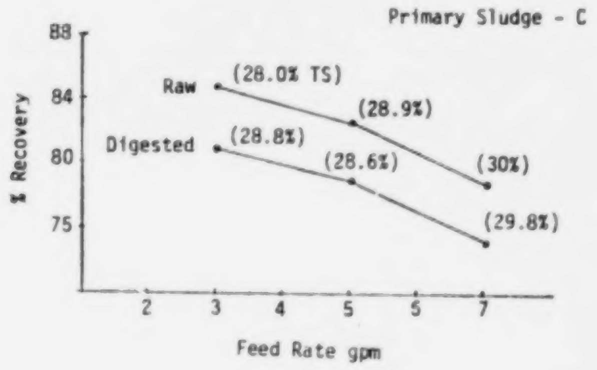


Figure 42

Relationship Between Cake Dryness and Percent Recovery(152)

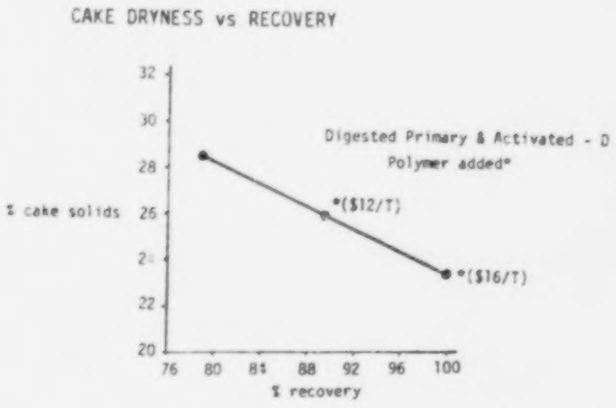
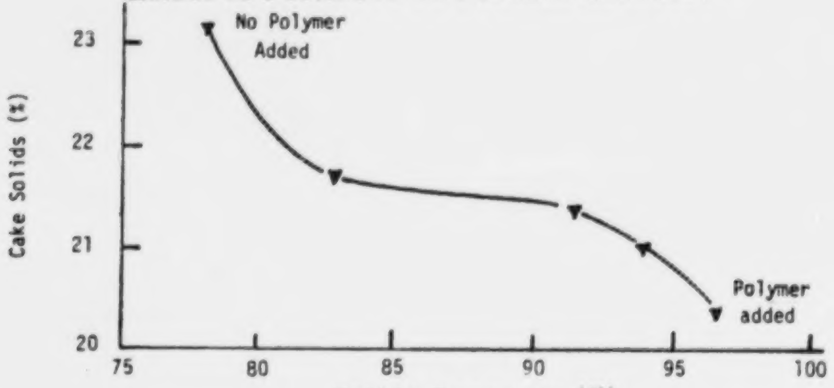


Figure 43

Effect of Polymers on Percent Recovery(153)



Solids Recovery (%)

Sludge cake moisture is an important factor in centrifugation of sludge. The percent moisture requirement of the cake is generally dictated by the method of cake disposal. Normally, reduction of moisture below 75 to 80% is not economically feasible. When incineration is used for final disposal of the sludge, lower moisture content of 60 to 70% is generally required. At lower moisture content sludge incineration may not need auxilliary fuel. Typical characteristics of the centrifuge sludge cake are presented in Table 60.

TABLE 60

Characteristics of Centrifuge Sludge Cake(9)

Wastewater Sludge Type	Sludge Cake Characteristics Solids %	Solids Recovery %	Chemical Addition
Raw or digested primary	28-35	70-90	no
Above, plus trickling filter humus	20-30	80-95	yes
		60-75	no
Above, plus activated sludge instead of trickling filter humus	15-30	80-95	yes
		50-65	no

Table 61 presents summary results of various types of sludge dewatered by centrifugation (152).

TABLE 61
Summary of Results-- Sanitary Sludges(152)

Type Sludge	Cake Conc.	Recovery - %		Chem Cost
	% TS	w/o Chem	w/Chem	$/Ton
RP	28-35	85-90	95+	3-8
DP	25-35	80-90	95++	3-8
R (P + TF)	20-26	65-85	95+	6-16
D (P + TF)	18-25	60-85	95+	8-16
R (P + AS)	18-24	50-80	95+	6-20
D (P + AS)	18-24	50-70	95+	10-20

R = Raw
D = Digested
P = Primary
RP = Raw Primary
DP = Digested Primary
TF = Trickling Filter
AS = Activated Sludge

A summary of the advantages claimed for sludge centrifugation includes the following: (1) lower capital cost than other mechanical dewatering equipment; (2) lower space requirement; (3) no need for chemical conditioning of the sludge; (4) chemical dosage rate not critical (operators can proceed with only intermittent dosage of chemicals); (5) minimal odor; (6) supervision requirement minimal; (7) simple and easy unit operation; and (8) high degree of flexibility of the unit (e.g. it can handle dilute or thick feed equally well; and can function as a thickening or dewatering device).

The disadvantages of sludge centrifugation as stated by Burd (17) are: (1) without use of chemicals the solids capture is often poor, and chemical cost could be substantial, (2) screening must often be used to remove the trash from the centrifuge feed, and (3) cake solids are often lower than those resulting from vacuum filtration.

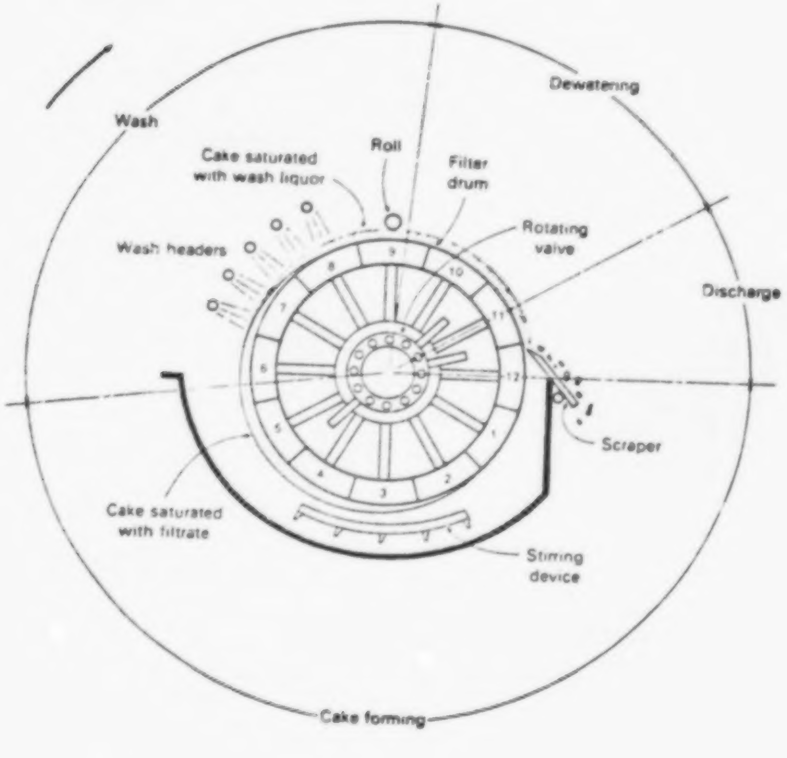
Vacuum Filtration

Vacuum filtration of sludge is the most common mechanical method of dewatering used in both municipal and industrial waste treatment plants. It has been used very successfully in the West Southwest Wastewater Treatment Plant, Chicago, Illinois with 96 operating units. Reports of the four leading manufacturers of vacuum filters in Dec., 1967, showed that over 1523 units were installed for all types of sludges originating from municipal wastewater treatment plants, alone (9). According to Burd (17) the rapid increase in the use of vacuum filters in wastewater treatment in the past decade is believed to be due to: (1) increased cost of the alternative methods of sludge dewatering; (2) development of self-cleaning filter media; and (3) the increased use of incineration as the final disposal technique.

The sole purpose for the use of a vacuum filter is to reduce the water content of a sludge, whether the sludge is raw, digested, or elutriated. The solids content is increased to a level of 25 to 30% by filtration (14). Various types of vacuum filters used for this purpose are:(1) drum-type filters, which were the first continuous filters using scraper-discharge mechanism, with functioning zones, such as cake forming zone, wash zone, dewatering zone, and discharge zone (See Figure 44); (2) string-discharge filters, utilizing closely spaced (about 0.5 to 1.3 cm apart) strings which pass around the filter drum and medium, and a set of discharge and return rolls to carry the filter cake free of the medium and discharge it; and (3) belt-type filters, utilizing a traveling woven cloth or metal belt serving as a filter medium. The discharge mechanism is the

Figure 44

Diagrammatic Cross Section of Rotary Drum Vacuum Filter(14)


Wash
Dewatering
Roll
Cake saturated with wash liquor
Filter drum
Rotating valve
Wash headers
Discharge
Scraper
Cake saturated with filtrate
Stirring device
Cake forming
1
2
3
4
5
6
7
8
9
10
11
12

same as for the string-discharge filters. The filter medium is washed from both sides to minimize any blinding effect of the sludge solids. A schematic of a belt-type filter is shown in Figure 45. Coil-type filters use two layers of stainless steel coil springs arranged in corduroy fashion around the drum. These springs act as the filter medium. After the dewatering cycle is completed the two layers of springs are separated from each other in such a manner that the filtered sludge cake is lifted off the lower layer of the coil springs and is discharged from the upper layer with the aid of a positioned time bar.

Factors affecting dewaterability, of the sludge as stated by Burd (17) are: (1) sludge solids content, (2) sludge age and temperature, (3) sludge and filtrate viscosity, (4) sludge compressibility, and (5) the nature of the sludge solids including the volatile content, size, shape, electrical charge, density, content of bound water and whether or not the sludge has been exposed to biological treatment.

Factors influencing the operating conditions of a vacuum filter have been reported (17) to be: (1) vacuum pressure applied, (2) filter submergence, (3) type of filter media, (4) degree of agitation, (5) drum speed, and (6) conditioning of sludge prior to filtration.

Figure 45

Belt-type filters have facilities for continuous intermittent washing of belt media.(9)

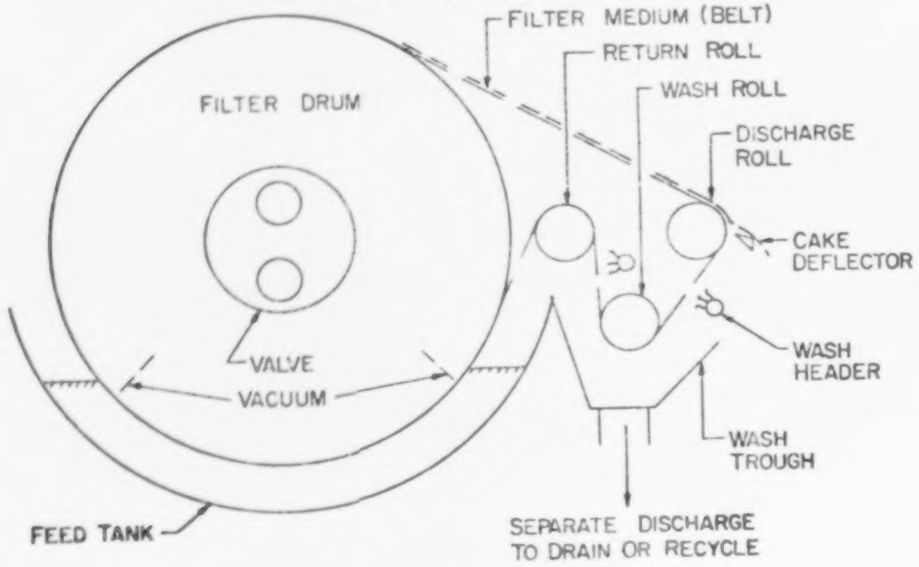

FILTER MEDIUM (BELT)
RETURN ROLL
WASH ROLL
DISCHARGE ROLL
FILTER DRUM
CAKE DEFLECTOR
WASH HEADER
VALVE
VACUUM
WASH TROUGH
FEED TANK
SEPARATE DISCHARGE TO DRAIN OR RECYCLE

Figure 46

Filtration rate versus solids concentration; leaf test data for primary-activated sludge, East Lansing, Mich.; medium, polyethylene 802 HF; vacuum, 20 inc. Hg; cycle, 3.6 min; submergence, 25 percent; chemicals, 2 1/2 percent $FeCl_3$ and 10 percent lime. (154)

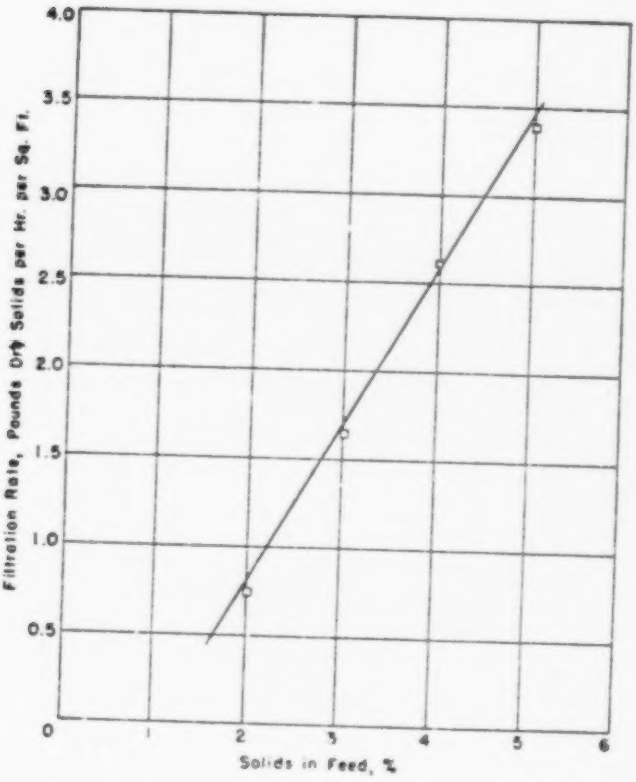


Figure 47

Example of effect on cake moisture of elapsed time after thickening sludge. (1.12-percent activated solids.)(82)

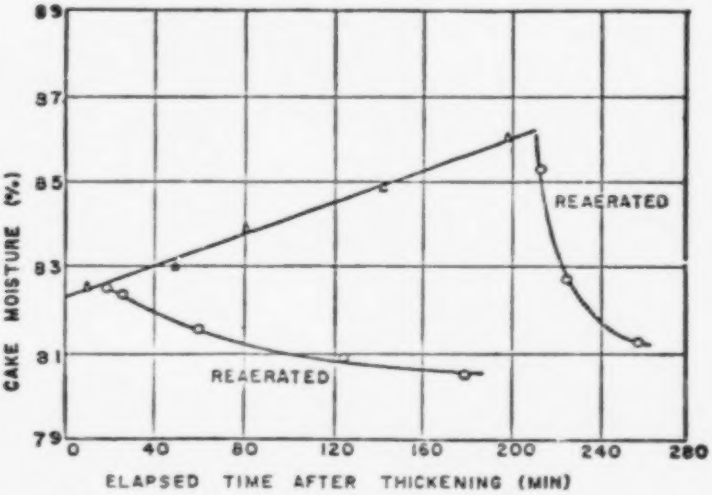
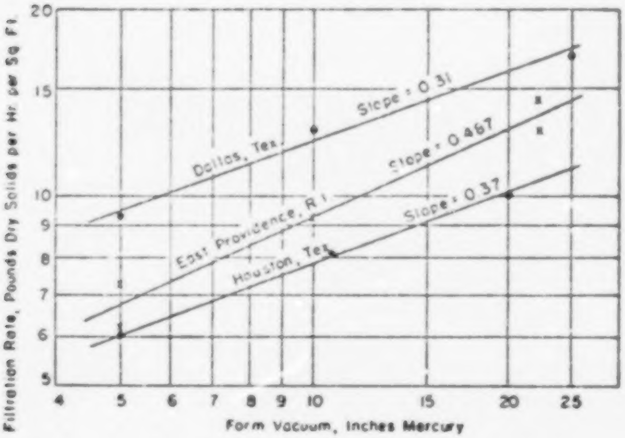


Figure 48

Filtration rate versus form vacuum; pilot-plant data.(154)



Feed sludge concentration is the most important variable in vacuum filtration. In general an increase in feed sludge solids content increases the vacuum filtration rate (shown in Figure 46). Although filter production increases as feed solids content increases, feed solids concentration must be limited to 8 to 10%, beyond which chemical conditioning and sludge distribution becomes difficult (17).

The effect of sludge age on filtration rate and cake moisture content was investigated by Ettelt and Kennedy (82). As shown in Figure 47 an increase in sludge age resulted in a high cake moisture content. It was also observed that freshening of the aged sludge reduces the cake moisture content dramatically.

Schempman (154) has presented data showing the relationship between the amount of pressure applied and the filter cake yield, as shown in Figure 48.

Pretreatment of most sludges is practiced commonly to reduce the moisture content of the sludge prior to vacuum filtration. This is accomplished by thickening, which produces higher solids content; or by elutriation as in the case of digested sludge, to reduce chemical demands used for conditioning. Chemical conditioning of sludge, as frequently practiced, is used to enhance the dewaterability of the sludge cake. Although a long list of the chemicals used for conditioning of the sludge is available in the literature, the most frequently used chemicals reported are ferric chloride; ferric chloride and lime; and cationic polyelectrolytes. The chemical dosage used for various types of sludges and the resulting cake moisture contents are presented in Table 62 and Table 63.

TABLE 62 (17)

Type of Sludge	Dose Rate %	Yield (Lbs/sq-ft/hr)	Cake Moisture %
Raw primary or raw primary and filter humus	0.2 - 1.2	6 - 20	63 - 72
Digested primary	0.2 - 1.5	4 - 15	66 - 74
Digested primary and activated	0.5 - 2.0	4 - 8	68 - 76

TABLE 63

Type of Sludge	Chemical Dose Rate(17) % Ferric Chloride	Lime	Yield (Lbs/sq ft/hr)	Cake Moisture %
1. Raw primary	2.1	8.8	6.9	69.0
2. Digested primary	3.8	12.1	7.2	73.0
3. Elutriated digested primary	3.4	-0-	7.5	69.0
4. Raw primary + filter humus	2.6	11.0	7.1	75.0
5. Raw primary + activated sludge	2.6	10.1	4.5	77.5
6. Raw activated sludge	7.5	-0-	-	84.0
7. Digested primary + filter humus	5.3	15.0	4.6	77.5
8. Digested primary + activated sludge	5.6	18.6	4.0	78.5
9. Elutriated digested primary + activated sludge:				
(a) Average w/o lime	8.4	-0-	3.8	79.0
(b) Average w/lime	2.5	6.2	3.8	76.2

Advantages claimed for use of vacuum filters in sludge dewatering include: (1) a filter cake of relatively low moisture content which is important when sludge is to be incinerated; (2) high solids recovery; (3) small space requirement; and (4) applicability to all types of sludges.

The disadvantages of vacuum filters reportedly are: (1) high cost of chemicals required for conditioning; (2) frequent shutdown of operation for cleaning purposes; (3) odor from filtration of raw sludge; and (4) requirement of highly trained operators.

Filter Presses and Plug Presses

A review of the literature reveals that use of the filter press for municipal sludge dewatering is not very common in the U.S. because of the high cost of manual labor and maintenance of this system. However, its application in Europe is very common. Vater (155) has stated that "of all available mechanical sludge dewatering equipment, the filter press yields the greatest possible cake solids content. This cake can be ground without previous drying and can be incinerated with little or no supplemental heat......Recently, improved construction, using automatic cake removal has made this process popular in many European communities."

The filter press uses the principle of free water drainage followed by the application of low pressure. Filter presses are operated in batches and chemicals have generally been used for sludge conditioning. Carnes and Eller (13) reported that by employing the filter press system, cake with as high as 50% solids may be obtained, if filter aids such as diatomaceous earth or ferric chlorides are used. The capital investment for filter presses is believed to be higher than for centrifuges or vacuum filters. However, it is a much more attractive method of dewatering if sludge is incinerated; because fly ash may be recycled and used for precoating or as a conditioning agent.

The filter press is still used by industry in the U.S. for the main reason that it can handle all types of sludges. Results of filter press dewatering of several industrial sludges are presented in Table 64 (13).

Plug presses are similar in principle to filter presses. Pressing techniques are limited to a two-stage dewatering system, generally installed prior to incineration. Plug presses have the advantages of free water drainage followed by the application of low pressure, thus minimizing the need for chemicals. The two proprietary systems using this technique are the "Roto-Plug" and "DEG Solids Concentrator." These units have been used in smaller communities and in industries. The main objectives in these systems are: (1) to avoid the critical pressures that would break the structure of the sludge solids and blind the filter media, and (2) to avoid large dosages of flocculants necessary to builda firm solids structure (17,156).

The dewatering of the sludge by the filter press is generally accomplished in successive stages with increasing pressure in each stage. Sludge conditioning depends on the presence of natural flocs. It has been found that conditioning is unnecessary for fresh sludge where an abundance of fresh floc exists, but is desirable for digested or other aged sludge (157).

TABLE 64

Result of Pilot-Scale Testing of Filter Press[13]

	Sludge			
Properties	Waste Activated	Digested Activated	Primary	Primary/ Activated
Feed				
pH	9.5	11.3	10.9	12.1
Solids (%)	1.2	1.5	1.3	1.4
Chemicals (%)	20.7	24.7	19.1	23.7
Water (%)	62.5	60.5	64.0	65.5
Sludge (%)	16.7	17.6	15.3	25.7
Total cake (%)	37.4	42.3	34.4	49.4

Advantages claimed for the system include: (1) minimal sludge conditioning requirements; (2) low power requirements; (3) low capital cost of the equipment; (4) low area requirement; and (5) simple system operation (156). However these systems have not received wide application because the resultant cake is not sufficiently dry and the solids content of the separated water is very high.

Vibration

Reports have shown that sludge dewatering by mechanical or sonic vibration has been investigated in a number of wastewater treatment plants in the U.S., as well as overseas (14,17,158).

Eckenfelder and Spohr (158) reported on sludge thickening using the "Heymann" process. This process consists of a series of vibrating screens and a rotary press. Although the simplicity and small size of this system is very advantageous; the solids capture efficiency is very low, the dewatering performance of the system is unsatisfactory, and the maintenance costs of the screens are generally high.

Kiess (159) has discussed the application of "Rhewm" sonic vibrating screen filters. This system consists of a set of three screens in series. A vibrating coarse screen (8 to 24 mm. mesh) removing only 2% of the sludge solids; sonic screen (1.2-2 mm. mesh) capable of removing 23% of the sludge solids; and sonic filter (0.1-0.5 mm. mesh) removing 55% of the total solids. Dewatering efficiency of this process is believed to depend on such factors as solids loading, sludge particles, size distribution, type of sludge and the angle of sludge discharge to the filter cloth. The resulting dewatered sludge contained 20 to 25% solids. The filtrate though containing a high percentage of solids was found to have good settling characteristics. Advantages and disadvantages of this system are similar to those of the "Heymann" process.

Heat Drying

The main objective in heat drying of the sludge is to convert it from an undesirable state to a useable form, such as fertilizer or soil conditioner. Sludge is generally dewatered to a 10 to 20% moisture content utilizing heat drying facilities. Heat drying to a low moisture content permits the end product to grind well, reduces sludge weight and odor, destroys pathogenic microorganisms preventing further biological action, and most important of all, provides an ultimate means of sludge disposal by recycling the organic material back into the land.

The various types of equipment used for sludge drying include: (1) flash-drying system, (2) multiple hearth dryer, (3) rotary kiln dryer, and (4) atomized spray dryer. All of the above drying facilities have been used to dewater the sludge to a 10% moisture content, but the most common type used in wastewater treatment sludge has been the flash-drying system. Because of the high costs involved in sludge drying, sludge is generally dewatered by mechanical means prior to drying.

The flash drying operation involves pulverizing the sludge in a cage mill in the presence of a hot gas stream (1300°F). The wet sludge cake is generally blended and mixed with recycled drier sludge, thus bringing the moisture content to about 50%. The mixed sludge and the stream of hot gases are then forced up a duct where drying takes place. The equipment is designed so that enough contact time between the sludge and the hot gases is provided, thus accomplishing mass transfer of moisture from the sludge to the gases. The separation of the dried sludge from the gases and vapor then takes place in a cyclon (14, 14, 156). Dried sludge having moisture content as low as 8% can be obtained in this process.

Multiple hearth drying of sludge utilizes basically a multiple hearth incinerator with a few modifications to the basic furnace design, including a fuel burner at the top and bottom hearth plus parallel downward flow of both sludge and gases. During operation the sludge solids flow downward through the furnace, the gases become cooler and solids become drier. According to Burd (17) at the point of exit from the furnace the gas temperature reaches about 385°F and the solids temperature about 100°F.

Rotary kiln driers have been used in municipal water treatment plants for calcining of lime sludge. Dayton, Ohio; Miami, Florida; and Lansing, Michigan are examples. A rotary kiln drier consists of a cylindrical drum, cyclone dust collector, and a gas deodorizing incinerator. The mixture of the wet and previously dried sludge is entered into one end of the rotating drum through which the hot gases are passed. As the sludge solids are transported towards the outlet they come in contact with the hot gases and lose their moisture. The dried sludge solids emerge at the opposite end of the drum where hot gases are entering. This process employs a countercurrent flow principle (14). Burd has reported that the system would work as well employing parallel non-countercurrent flow principle, in which case both sludge and hot gases are introduced into the drum from the same end. Gases that are emerging from the drum contain certain amounts of fine sludge particles. Separation of these particles takes place in a cyclone precipitator.

The atomized drier uses a high speed centrifuge bowl located at the top into which the liquid sludge is fed. The object of the centrifuge is to atomize the sludge into fine particles and then spray them over a drying chamber. Hot gases enter into the chamber from the top. As the atomized particles come in contact with the hot gases, they release moisture to the hot gases and then drop to the bottom part of the drying chamber.

Sludge drying temperature commonly used is about 700°F in comparison to complete incineration temperature of about 1200-1500°F. Odor control is an important factor associated with sludge drying. For complete elimination of odor the exhaust gases must reach approximately 1350°F. This is generally accomplished by reheating the exhaust gases. At lower temperature oxidation of the odor producing compound may occur in which case the product may have a very offensive odor. (14)

It appears that the trend from sludge drying has been shifted to sludge incineration, although incineration is not considered to be the ultimate disposal means. The major reason for the shift appears to be: (1) lack of existence of fertilizer market, and (2) capital and high fuel costs. Combustion (incineration) of combined sludge and municipal refuse is under consideration and is believed to improve the economics of sludge disposal.

SLUDGE TRANSPORTATION

Common methods for conveying the resulting liquid or dried sludge from the wastewater treatment plant to a final disposal site include transportation by: (1) barge; (2) pipeline; (3) truck; and (4) railroad.

Barging of the sludge is frequently used in conjunction with the ocean disposal of the sewage sludge. It is principally in coastal cities; namely, New York, Baltimore, and Philadelphia. Wastewater sludge disposed of at sea from the New York area is handled by a fleet of five self-propelled barges operated by the City of New York, having capacities ranging from 1200 to 3200 tons. Private firms also have contracts with the City of New York for barging sludge. The largest barge used is 226 ft. long, 56 ft. wide and has a 20 ft. draft. It has a capacity of 6300 tons, and the entire load is discharged in 30 minutes (160). The distance for sludge barging depends on the location of the treatment plant and the off-shore disposal area. The average round-trip distance for New York is approximately 30 miles, while the City of Philadelphia averages about 227 miles (160).

Sludge is generally stabilized and thickened to about 4 to 10% solids content prior to barging in order to reduce the cost of barging, to prevent pollution hazards and prevent septic conditions of sewage sludge during barging.

Approximately 4.5 million tons (on a wet basis) of wastewater sludge was barged to the sea in 1968. It was also projected that barging will increase significantly in the next ten years (160). Table 65 represents a summary of the quantities and estimated costs of various wastes

TABLE 65

Summary of Type, Amount and Estimated Costs of Wastes Disposed of in Pacific, Atlantic, and Gulf Coast Waters For the Year 1968(160)

Waste type	Pacific Coast		Atlantic Coast		Gulf Coast		Total		Total	
	Annual tonnage	Estimated cost$	Annual tonnage	Estimated cost $	Annual tonnage	Estimated cost $	Annual tonnage	Estimated cost $(e)	% Tonnage	% Cost
Dredging spoils	8,320,000	3,608,000	30,880,000(a)	16,810,000	13,000,000	3,228,000	52,200,000	23,646,000	84	63.5
Industrial wastes										
bulk	981,000	991,000	3,011,000	5,406,000	690,000	1,592,000	4,682,000	7,989,000	8	21.7
containerized	300	16,000	2,200	17,000	6,000	171,000	8,500	204,000	<1	<1
Refuse, garbage(b)	26,000	392,000					26,000	392,000	<1	1
Sewage sludge(c)			4,477,000	4,433,000			4,477,000	4,433,000	7	12
Miscellaneous	200	3,000					200	3,000	<1	<1
Construction and demolition debris			574,000	430,000			574,000	430,000	1	1
Explosives			15,200	235,000			15,200	235,000	<1	<1
Total, all wastes(d)	9,327,500	5,010,000	38,959,400	27,331,000	13,696,000	4,991,000	61,982,900	37,332,000	100	100

(a) Includes 200,000 tons of fly ash.
(b) At San Diego 4700 tons vessel garbage at $280,000 per year were discontinued in November 1968.
(c) Tonnage on wet basis. Assuming average 4.5 percent dry solids, this amounts to approximately 200,000 tons dry solids per year being barged to sea.
(d) Radioactive wastes omitted. There were no dumps during 1968. Average Annual disposal in 1969–1970 was 4.2 tons.
(e) Estimated costs were increased proportionately for each area from the original Tonnage/cost data.
* Revised and updated by James L. Verber, FDA.

barged to the sea for disposal in the Atlantic, Pacific, and Gulf coastal waters.

Barging of sludge is also used in Chicago, Illinois where the sludge is barged from the West-Southwest Waste Treatment Plant down the Illinois River to Fulton County, Illinois, approximately 200 miles from Chicago. Here it is pumped from the barge through 11 miles of pipeline to storage lagoons.

Pipeline transportation of liquid sludge is very common. It has been used for a variety of purposes including: (1) collection and transporting of sludge from a multiple wastewater treatment plants and sludge treatment processes to a centralized one such as Philadelphia, Chicago, etc.; (2) transport to a farm where sludge is used as a soil conditioner; (3) transportation of sludge for land reclamation, such as in San Diego, and New York; and (4) transportation of sludge to a disposal site at sea, such as Los Angeles.

In large cities, the practice of combining dewatering and ultimate disposal of wastewater sludge from various treatment plants into a single or centralized location has shown definite advantages. Pipeline transportation of sludge to the land disposal area has been practiced in major cities. San Diego hauled sludge by truck from the treatment plant to the land disposal area at a cost of $1.9 per 1000 lbs. in 1960. This cost was reduced to about one-fourth by building of a pipeline system (161, 162). New York City uses pipeline and barges to transport vast quantities of liquid sludge to several hundred acres of sandy soil, where the sludge is applied to a depth of 18" and allowed to dry and form a topsoil layer. (164) Data on long distance transporting of sludge via pipelines is presented in Table 66, and has been compiled from various sources appearing in the literature (163, 164, 165, 166, 167).

Pipeline transportation of sludge has definite advantages, as it allows flexibility in ultimate disposal techniques. It permits the relocation of large quantities of sludge away from land-short urban areas for final disposal. (Final disposal may be land spreading of the sludge as fertilizer or soil conditioner, lagooning, reclamation of abandoned strip mines or ocean disposal.) Since it is a closed system, it is a relatively trouble-free and odor-free operation. Pipelining of raw primary sludge is not recommended due to potential gases, grease and abrasion problems.

Friction loss is an important factor in design of sludge pipelines. Reported values of friction loss for digested sludge varies from 1 to 5 times that of water. Digested sludge exhibits non-Newtonian flow characteristics for solids concentration above 6 percent. In

TABLE 66

Long Distance Sludge Transportation via Pipelines

Location	Length (ft)	Diameter (in.)	Sludge	
			Type	Concentration (%)
Houston, Tex.	4,300	8	Activated	0.5-1
	10,000	4	Activated	0.5-1
	12,000	8	Activated	0.5-1
	21,000	6	Activated	0.5-1
	36,000	8	Activated	0.5-1
Kansas City, Mo.	35,000	12	Raw primary	
San Diego, Calif.		8	Digested secondary	6.0
Jersey City, N. J.	13,150	twin 6	Raw primary	0.85-1.55
Bay Park, N. Y.	8,000	10	Digested activated and primary	2.8
Rahway Valley, N. J.		8	Raw primary, some digested primary	2.8 5.0
Austin, Tex.		8	Activated	0.8
Knoxville, Tenn.	16,800	6	Raw primary and humus	0.55
Morgantown, W. Va.		2	Digested	Varies
Mogden, England	7,000	12	Digested	4.0-5.0
Birmingham, England	4,000	9 and 12	Digested	8.5-10.0
The Hague, Netherlands	7,000	8	Digested	4.0-5.0
Los Angeles, Calif.	7,500	24	Digested	3.73
Chicago, Illinois	17,000	14	Raw	1.0-2.0
	5,000	12	Raw	2.0-4.0
Cleveland, Ohio	13,000	12	Raw	3.0-4.0
Philadelphia, Pa.	5,000	8	Raw	3.0-4.0
Columbus, Ohio	5,000	-	-	4.0-5.0

non-Newtonian flow, friction head loss depends primarily on the viscosity of the liquid sludge, which in turn is related to the velocity of the flow; diameter of the pipe; and type, particle size distribution, and solids concentration of the sludge. The effect of solids concentration of the sludge on Hagen-Williams co-efficient (HWC) and the power to overcome the pipeline friction are shown in Table 67. The critical velocities of a sludge are affected by its solids content. Velocities greater than the critical will cause an excessive head loss due to an increase in friction. A wide range of operating velocities has been reported in the literature. However, velocities ranging from 5 to 8 ft./sec have been reported to be satisfactory. Extensive study on critical velocities of pipelines was made by Chou (24). Results of this study are shown in Table 68.

TABLE 67

Variation in Power Requirements with Concentration(164)

C(%)	D(in)	Q(cfs)	C_{HW}	Horsepower/mile
3.5	24	10.5	160	11.5
5.0	20	7.3	160	9.6
6.0	18	6.1	160	8.0
8.3	16	4.4	110	16.0
10.5	14	3.5	100	17.0

TABLE 68

Critical Velocities for Various Pipe Diameters(24)

Diameter (in.)	Critical Velocity (fps)	
	Lower	Upper
8	3.58	4.52
10	3.55	4.42
14	3.45	4.31
20	3.40	4.23

Brisbon (26) has reported that a decrease in temperature below 65°F caused a considerable increase in head loss, whereas a slight temperature increase above 65°F appeared to have very little influence in decreasing friction loss.

Truck transportation of liquid and dried sludge from the treatment plants to the final disposal site is a very common method, particularly in smaller treatment plants. Disposal areas are generally landfill, sanitary landfill, or farmland. Where liquid sludge is transported, tank trucks are usually equipped with a splash plate or distribution manifold to spread the sludge.

Railroad transportation of the wastewater treatment plant sludge is not very common. However, it has been practiced in Chicago, Illinois.

SLUDGE REDUCTION PROCESS

Sludge Incineration

A review of the literature indicated that incineration of wastewater sludge is rapidly increasing, particularly in large urban cities. Reasons for this rapid growth are primarily due to: (1) rapid increase of the cost and lack of land available for the alternative disposal methods; (2) the health aspects associated with conventional disposal methods are of increasing concern to the general public, consulting engineers, public health and municipal officials; and (3) increase in sludge production,pollution standards and growth of population has increased the pressure for complete or nearly complete "on site" disposal of solids.

Sludge is incinerated for two primary reasons: (1) volume reduction; and (2) solids reduction and sterilization. The end product of the sludge incinerator consists of water, gases such as CO_2, SO_2, NO_x; and inert ash. The problems involved in sludge incineration are air pollution,and disposal of the ash. However, it is believed that advancement in technology will eventually eliminate the air pollution problem, and the growing concern over the utilization of incinerator ashes and coal ashes will overcome the ash disposal problem.

Sludge combustion is effected by a number of factors, including: sludge moisture content; sludge calorific value; sludge volatile content; and sludge inert content. The efficiency of incineration increases as the sludge moisture content decreases. Sludge is generally dewatered to about 70% moisture content prior to incineration. Chemical conditioning agents are commonly employed to improve sludge dewatering facilities. It has been found that organic polymers used as sludge conditioners not only enhance sludge dewaterability, but also increase the efficiency of incineration operations as a result of increasing the calorific value of sludge (168).

Calorific value and volatile content of the sludge are very important parameters. They reflect the degree to which the sludge could maintain self-sustained combustion. As indicated in Table 9, raw sludge contains higher calorific values (about 10,000 Btu/pound) than digested sludge (about 5,000 Btu/pound). The volatile content of the sludge may be improved by a highly efficient degritting system. Using hydrocyclones, Burger (169) has removed about 95% of the plus 200-270 mesh inorganics at a specific gravity of 2.67, thus increasing the volatile content of the sludge from 70-75% to 80-85%. In general the higher the volatile content of the sludge the lower will be the auxilliary fuel requirement for combustion. The effect of the volatile content of the sludge on operating costs of incineration is shown in Figures 49 and 50.

Presence of compounds such as $CaCO_3$ or CaO increases the fuel requirement. These compounds react endothermically at combustion temperatures. The decomposition of CaO materially increases the thermal burdens (156).

It was stated previously that the end products of sludge combustion are water, gases and inert ash. Formation of water, CO_2 and SO_2 releases significant amounts of heat, as shown in Table 69. This indicates that the combustible elements of sewage sludge are found in the organic part of the sludge, such as grease, carbohydrates and proteins. Elemental composition of the sewage sludge compiled by Balakrishnan et al (156), is presented in Table 70.

TABLE 69

Combustion Reactions of Sewage Sludge

Reaction	Heat Release (Btu/lb)
1. Carbon + oxygen carbon dioxide $C + O_2 \dashrightarrow CO_2$ (1 lb) (2.67 lb) (3.67 lb)	14,500
2. Hydrogen + oxygen water $2H_2 + O_2 \dashrightarrow 2H_2O$ (1 lb) (7.94 lb) (8.94 lb)	62,000
3. Sulfur + oxygen sulfur dioxide $S \quad O_2 \dashrightarrow SO_2$ (1 lb) (1 lb) (2 lb)	4,500

Figure 49

Effect of Volatiles in Sludge on Fuel (Natural Gas) Cost(156)

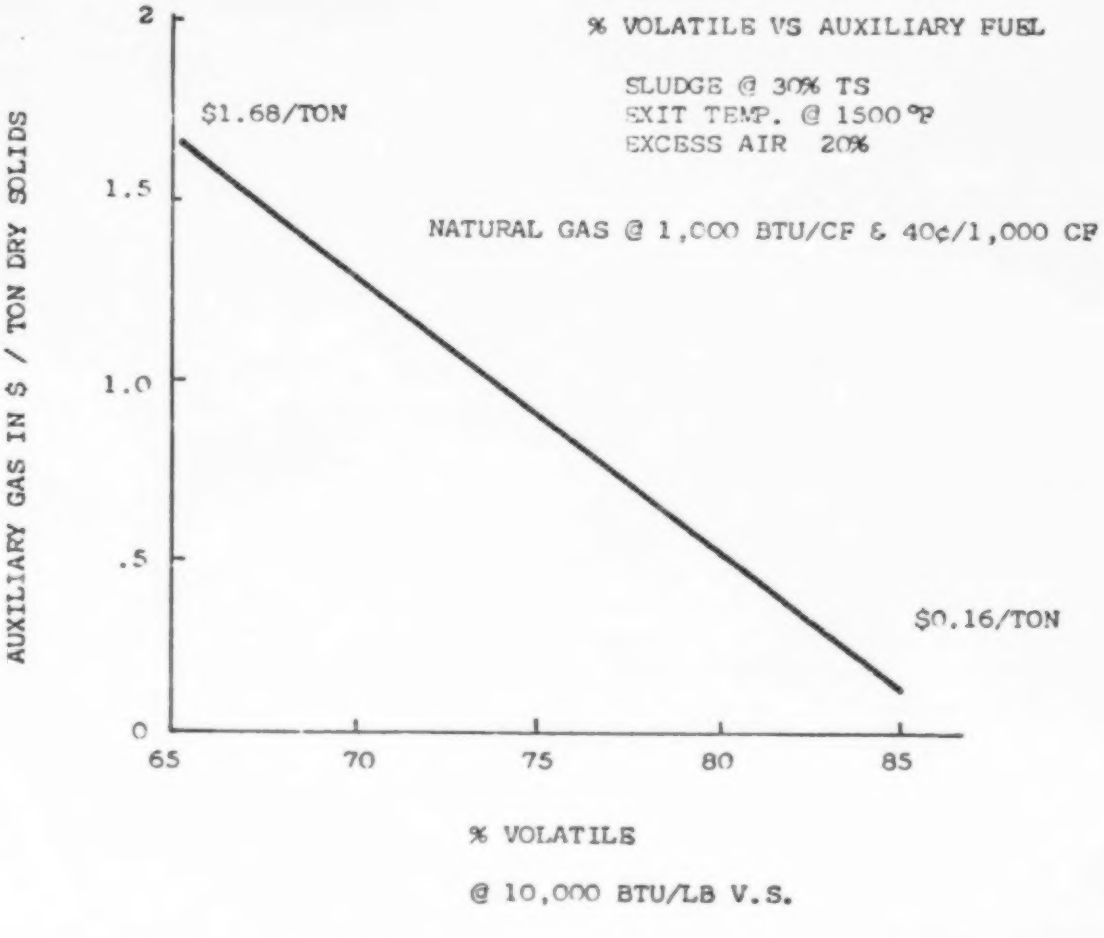


Figure 50

Effect of Volatiles in Sludge on Fuel (No. 2 Oil) Cost(156)

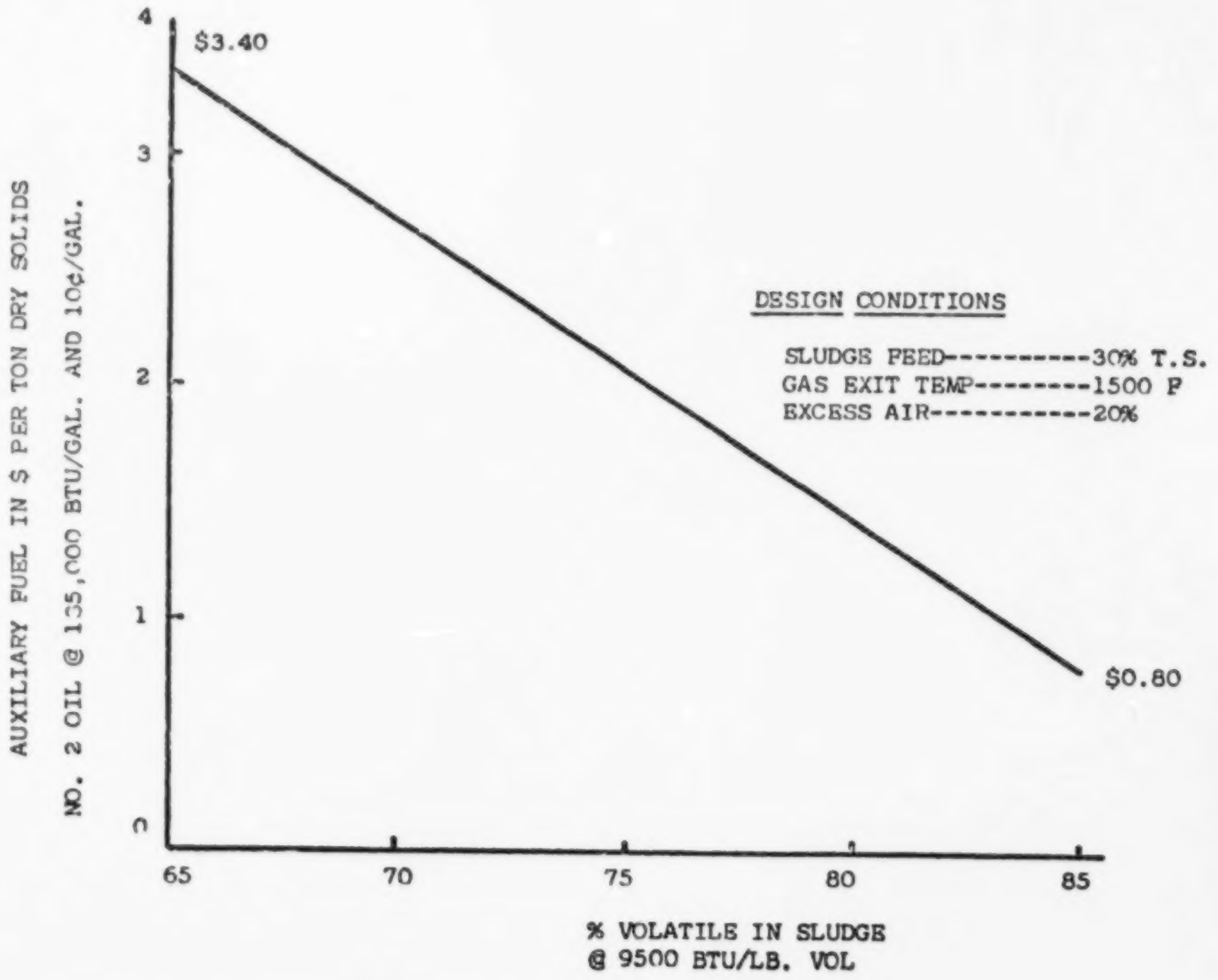


TABLE 70

Elemental Composition of Sewage Sludge(156)

Elemental Composition	Source* No. 1	No. 2	No. 3	No. 4
Carbon (%)	64.3	65.6	55.0	51.8
Hydrogen (%)	8.2	9.0	7.4	7.2
Oxygen (%)	21.0	20.9	33.4	38.0
Nitrogen (%)	4.3	3.4	3.1	3.0
Sulfur (%)	2.2	1.1	1.1	Trace
Volatalite (%)	47.9	72.5	51.4	82.0
V.S.S. (BTU/lb)	12,840	12,510	10,940	8,990
T.S.S. (BTU/lb)	6,160	9,080	5,620	7,380

*Source No 1 - Cleveland Southerly Plant, 1955
No. 2 - Detroit, Michigan, 1955-56
No. 3 - Minneapolis, Minnesota, 1955
No. 4 - New Rochelle, New York, 1960-62

A complete incineration process involves two steps: (1) drying, and (2) combustion. Fuel and air are continually utilized to complete the process. The auxilliary fuel requirement depends on such factors as sludge, Btu value, and heat required to insure odor control. Minimum deodorizing temperature of the sludge for conventional incinerators ranges from 1350 to 1400° F. The deodorizing temperature depends largely on the nature of the sludge as shown in Figure 51.

According to Balakrishnan (156) heat requirement of an incinerator system depends on efficiency of burning and excess air required. Total heat requirement of a system includes:

1. Heat required to raise the temperature of the sludge to 212°F; evaporating water from sludge; increasing the water vapor and air temperature of the gas; and increasing the temperature of dried volatiles to the ignition point.
2. Heat required to raise the temperature of the exhaust gas to the deodorizing temperature.
3. Heat required to raise the temperature of the air supply required for burning plus excess air.
4. Heat losses due to radiation.
5. Cooling air losses.
6. Heat required for other endothermic reactions taking place.

The moisture content of the sludge together with its volatile solids content dictates the autogenous combustion condition of an incineration operation. As shown in Figure 52 at 25% solids content the combustion product and moisture temperature will be raised as high as 900°F. This temperature, however, is not enough to deodorize the stack gases.

On the other hand, a rotary kiln can operate over a wide range of 7 to 70% solids content, whereas a fluidized bed reactor and atomized spray system require lower solids levels, ranging from 2 to 10 percent (17).

Drying and combustion has been practiced in separate pieces of equipment or successively in the same unit. A wide variety of sludge drying and combustion equipment are presently available. These include: (1) traveling-grate furnaces; (2) rotary-kiln type furnaces; (3) multiple hearth furnaces; (4) fluidized bed units; (5) flash-drying units; (6) wet-oxidation units; and (7) atomized suspension units. The principle variation between these systems lies on the requirement for heating, excess air, and the efficiency of utilizing the waste gases. A schematic of the two major types of incinerators are presented in Figure 53.

Figure 51

Relationship of Odor Level in Stack Gases to Highest Process Temperature Encountered[(156)]

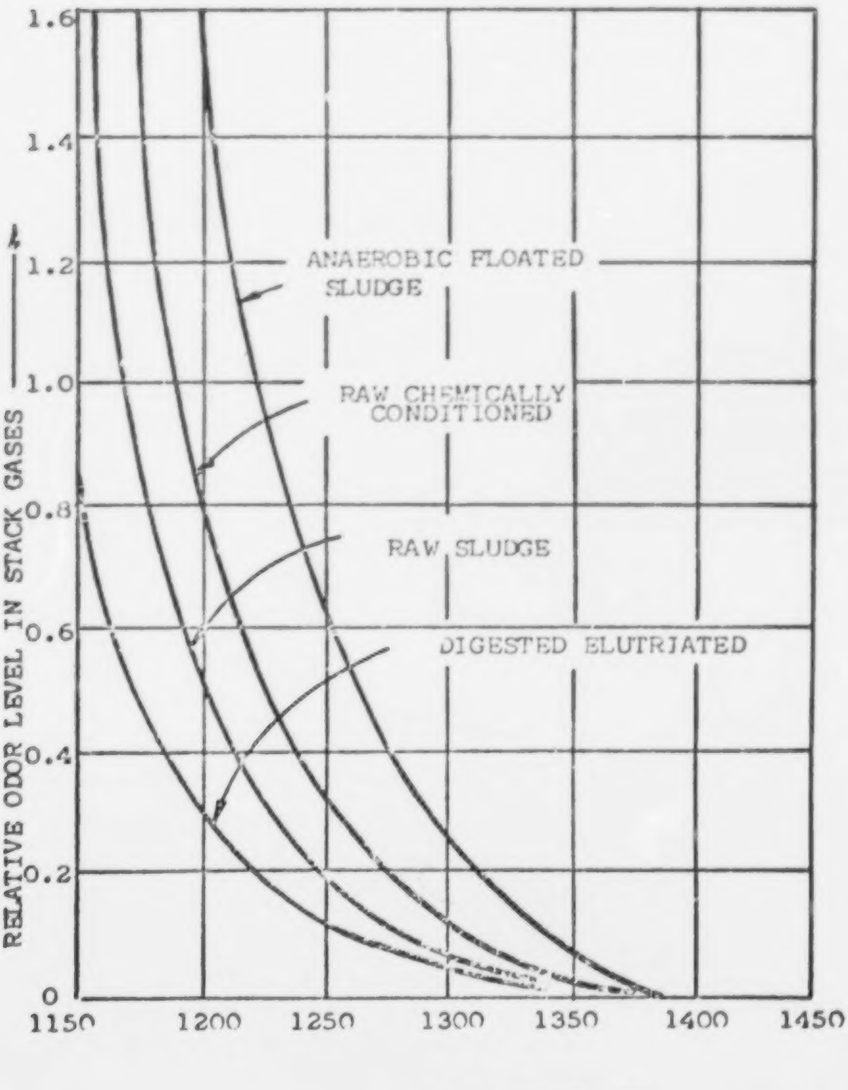


Figure 52

Equilibrium Curves Relating Combustion Temperature to Cake Concentration(156)

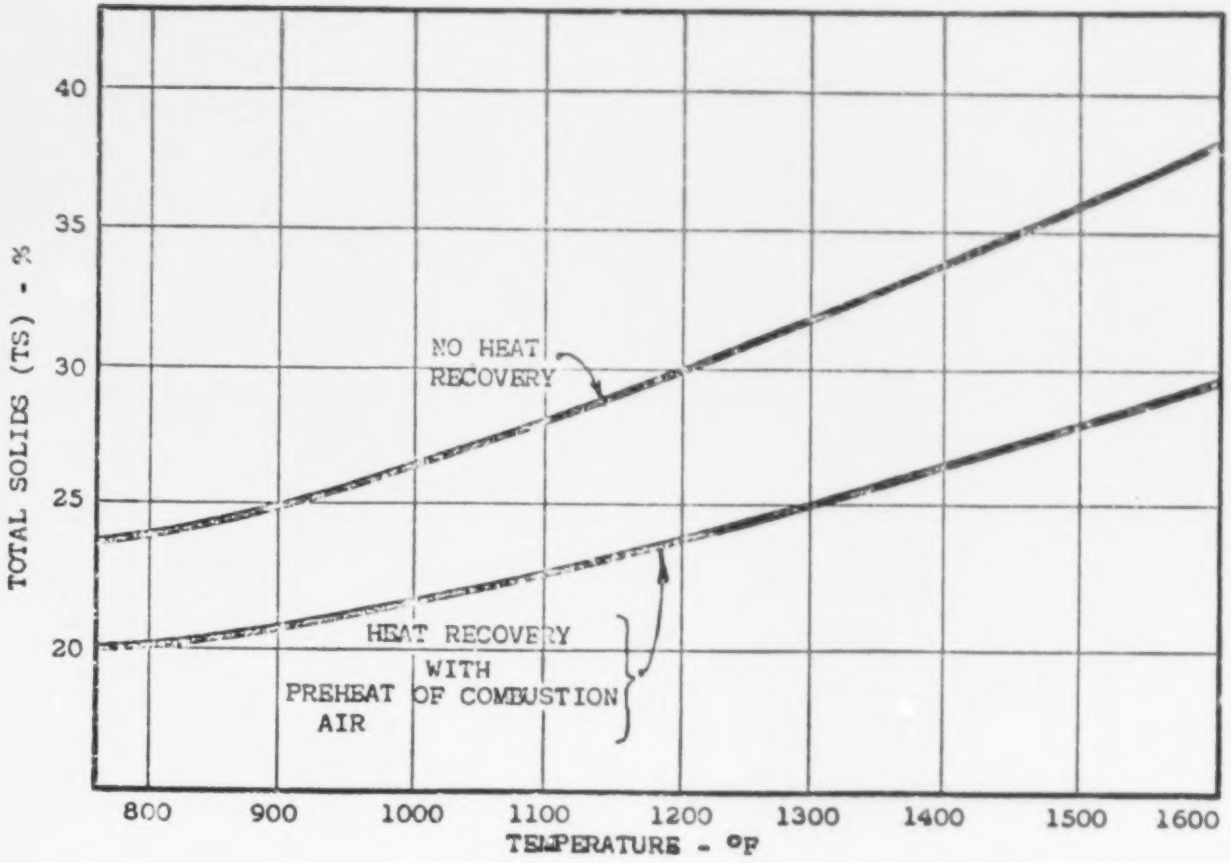
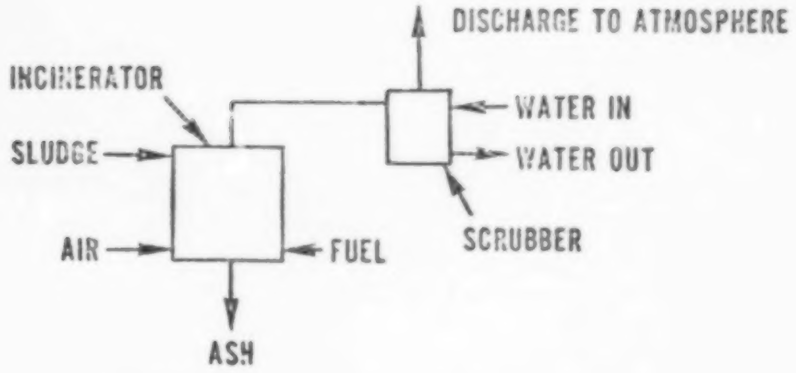
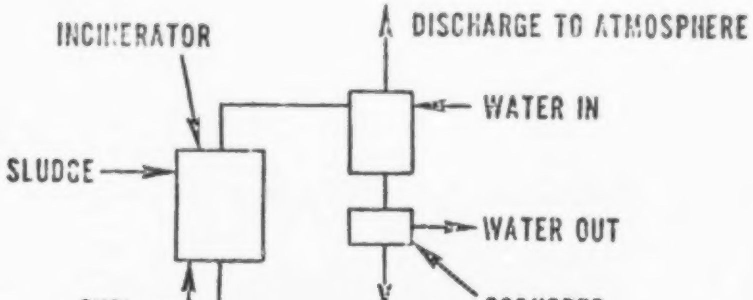


Figure 53

Schematic Representation of Incinerator Types[170]


DISCHARGE TO ATMOSPHERE
INCINERATOR
SLUDGE
WATER IN
WATER OUT
SCRUBBER
AIR
FUEL
ASH

(1a) Multiple Hearth Incinerator


DISCHARGE TO ATMOSPHERE
INCINERATOR
WATER IN
SLUDGE
WATER OUT
FUEL
AIR
ASH
SCRUBBER

(1b) Fluidized Bed Incinerator

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The literature reveals that sludge incineration is being adopted by many municipalities and industries despite the high capital cost of the system. The major types of incinerators that have been used are multiple hearth and flash-drying units. However, since the early 1960's wet-oxidation and fluidized bed systems have gained much popularity.

Advantages claimed for sludge incineration include: (1) greater reduction of sludge volume; (2) complete or nearly complete combustion of organics; (3) complete destruction of pathogenic organisms; and (4) an end product that is an inert ash creating no disposal problem.

A survey conducted on the attitude of consulting engineers regarding sludge incineration showed that the overall attitude of the consulting engineers was acceptance and even eagerness to employ incineration. Further, they felt that grease, oils, screenings, and organic industrial wastes could best be disposed of by incineration (156).

In regard to the continued use of sludge incineration, Burd (17) has stated that ".......with or without design improvements, incineration is the one sludge disposal process that, without a doubt, has a bright future because it meets future sludge disposal criteria."

Recently an extensive observation was made by the EPA Task Force on Sewage Sludge Incineration(170). Conclusions of these observations were:

1. The present incinerator systems which are equipped with air pollution control devices to meet the existing air quality standards have been shown to produce acceptable stack emissions of particulate matter, nitrogen oxides, sulfur oxides, and odor when operated properly. However, it was found that most existing sludge incinerators did not incorporate high efficiency particulate matter control devices.
2. Small, but measurable, quantities of toxic materials were found in input sludge, stack emissions, scrubber water, and incinerator residue.
3. Small, but measurable, amounts of specific organic chemical compounds, including various kinds of pesticides and PCB (polychlorinated biphenyls) were found in all of the sludge samples analyzed. These compounds may be emitted from the stacks when combustion conditions are poor.
4. The potential for health effects associated with sewage sludge incineration cannot be established accurately, because:

(1) insufficient health effect data relating to low atmospheric concentration of suspected pollutant material such as heavy metals, organic pesticides and PCB is available, and (2) sophisticated methods for proper sampling and analysis of stack gases are not available to produce accurate information regarding the quantity, size, distribution, and constituents quality related to size of the particulate matter emitted by sewage sludge incinerators.

Pyrolysis

Pyrolysis of wastewater sludge and refuse has recently been investigated as a substitute for incineration. It functions similarly to an incinerator as far as reduction of volume and stabilization of wastewater sludge is concerned. Its advantages over incineration are: (1) a useful by-product is produced, and (2) air pollution is eliminated. In general, the basic purpose in pyrolyzing the sludge is to decompose complex organisms to simpler materials (17). In the case of refuse solids, useful end products and by-products, such as combustible gas for boiler furnace fuel, elemental carbon, tar, resins and various acids could be obtained at 1200°F temperature (17).

Beeckmans and Ng (171) have investigated pyrolysis of activated sludge to produce a pyrolysate with an appreciably higher absorbing capacity than fly ash when used for the reduction of residual oxidizable material in the effluent of wastewater treatment plants. The pyrolysis unit used consisted of a closed, vertical stainless steel cylinder, with internal dimensions of 8 inches diameter by 18 inches high, containing six equally spaced hearths. The sludge was introduced continuously at the top of the unit by means of a feed screw, and the pyrolysate was continuously removed from the bottom by a vertical exit tube immersed in water. The sludge was processed through the unit by the raking action of off-center pairs of rabble arms attached to a central rotating shaft, with one pair of arms per hearth. The motion of the rabble arms pushed the sludge towards the periphery of the unit and toward its center, on alternate hearths. Suitably placed holes in the hearths then permitted the sludge to fall onto the next hearth beneath. A controlled flow of oxygen-deficient gas (generally below 2% O_2) was maintained in the furnace by drawing in the combustion products of a propane flame through an opening near the top. This was accomplished by a suction pump which was connected via a condensate trap and a condenser, to the bottom of the unit. The flow of gases was thus concurrent with the sludge.

Tables 71 to 74 present the results of their investigation. The conclusions drawn were: (1) for maximum carbon content in the pyrolsate, the oxygen content of the furnace gases should not exceed 2% at the top of the furnace; (2) sludge residence time should be approximately 90 minutes; (3) sludge feed rate should be about 12.5 g/min. (wet basis); (4) the input gas flow rate should be 25 liters/min.; and (5) pyrolyzed sewage sludge is intermediate in its absorption capacity between fly ash and activated carbon.

TABLE 71
Effect of Oxygen Concentration in the Purge Gas on the Carbon Content of the Pyrolysate[a] (171)

O_2 in inlet gas, %	C in pyrolysate, %
2.0	10.2[b]
4.2	4.6[b]
10.0	0.2[b]

[a] Input air flow, 25 liters/min.; residence time, 120 min.; sludge feed rate, 9.4 g./min.; bottom temperature, 1290°F.

[b] Average of five runs.

TABLE 72
Effect of Residence Time and Sludge Feed Rate on Carbon Content of Pyrolysate[a] (171)

Input air flow, liter/min.	Residence time, min.	Sludge feed rate, g./min.	C in pyrolysate, %
25	50	22.0	Pyrolysis incomplete
25	90	12.5	14.1[b]
25	120	9.4	10.2[b]
25	150	7.6	8.7[b]
15	90	12.5	10.7[b]
15	120	9.4	8.5[b]
15	150	7.6	8.4[b]

[a] Oxygen in inlet gas, 2%; bottom temperature, 1290°F.

[b] Average of four runs.

TABLE 73
Effect of Purge Gas Flow Rate on Carbon Content of the Pyrolysate[a] (171)

Input air flow, liter/min.	C in pyrolysate, %
15	8.5[b]
25	10.2[b]
30	8.4[b]
60	4.1[b]

[a] Oxygen in inlet gas, 2%; residence time, 120 min.; bottom temperature, 1290°F.

[b] Average of four runs.

TABLE 74
Results of COD Adsorption Tests,[a] Initial COD 53.5 mg./liter (171)

Adsorbent	Activated carbon	Pyrolyzed product, % C				Fly ash
		14.3	13.25	10.7	5.3	
Final COD, mg/liter	10.2	32.6	32.9	36.1	41.4	49.8
Removal, %	81.0	39.1	38.5	32.5	22.5	6.8

[a] Contact time, 24 hr.

ULTIMATE DISPOSAL AND/OR UTILIZATION OF MUNICIPAL WASTEWATER SLUDGES

The ultimate disposal of the vast quantities of sludge being generated throughout the U.S. is one of the most complex problems facing sanitary engineers today. The sludge disposal problem will continue to grow because of: more demanding water, air, and land pollution control standards; lack of land availability resulting from rapid growth of urbanized communities; public awareness of the health aspects associated with disposal of raw sludge; growth of population; and advancement of the technology in manufacturing more sophisticated wastewater treatment facilities to meet the present and future standards. This will result in a high degree of solids removal, and a larger quantity of solids requiring disposal.

Numerous methods for disposal or utilization of the municipal sludge have been practiced. These methods are summarized in Table 75.

Ultimate disposal of the sludge is the final step in the process. In some instances this transforms the sludge and then places it at its final site. The criteria to be followed for selection of the ultimate disposal method have been discussed by Smith (172). These criteria are: (1) the ultimate disposal method must be in accordance with State, interstate, and Federal Water Quality Office requirements; (2) the ultimate disposal method should not result in any significant degradation of surface or ground water, air, or land surfaces; (3) no sludge residue, grit, ash or other solids should be discharged into the receiving waters or plant effluents; (4) sludge disposal in ocean waters is not recommended as toxic metals may be transmitted to the aquatic food chain, and (5) sludge must be stabilized prior to spreading on land.

The major objective in this part of the study is to: (1) review briefly the conventional methods used for disposal and utilization of municipal sludge; and (2) evaluate these methods from aesthetic, economic and pollution hazards viewpoints.

Ocean Disposal of Wastewater Sludges

For most coastal cities discharge of wastewater sludge has been found to be very economical. Sludge with solids content ranging from 3 to 10% have been disposed of in the sea by barges from New York, New Jersey and Philadelphia. Metropolitan New York has been barging and dumping its wastewater sludge (about 5 million

TABLE 75

PRESENT METHODS OF MUNICIPAL SLUDGE DISPOSAL AND/OR UTILIZATION

Wastewater Treatment	Water Treatment
1. Ocean dumping or discharging	1. Direct discharge to streams, ocean or lake.
2. Land spreading of liquid sludge.	2. Lagooning of the sludge.
3. Land reclamation.	3. Agriculture utilization.
4. Lagooning and landfilling.	4. Discharge to sewers.
5. Disposal of dried sludge as fertilizer or soil conditioner.	5. Disposal in sanitary landfill.
6. Underground disposal.	6. Application of sludge to strip mines.
7. Incineration and landfill of ash.	7. By-product recovery.
8. By-product recovery.	

cubic yards) for over 40 years at a disposal site a few miles from the entrance to New York harbor and near the coasts of New Jersey and Long Island (6). On the Pacific coast, barges are not used; but, sludge is discharged into the sea through submarine outfalls. Approximately 650,000 lbs. per day of digested wastewater solids are discharged to the sea from the Los Angeles Metropolitan area. About 50 percent of 325,000 lbs. per day is discharged from the Hyperion Treatment Plant of the City of Los Angeles into Santa Monica Bay in 300 ft. of water 7 miles from shore via a 22" I.D. conduit. Wastewater sludge is also discharged to the sea from West Point Plant, Seattle, Washington; the West Point outfall extends 3650 ft. offshore to the diffusers and a depth of 230 ft. (173)

Most coastal cities have selected ocean disposal of sludge because of its favorable economics as compared with the alternative methods. In general, the cost of ocean sludge disposal, including barging and sludge treatment, ranges from 17 to 27 dollars per ton on a dry solids basis.

Other advantages of ocean disposal of the sludge for coastal cities include: (1) complete removal of the sludge from treatment plants; (2) a nuisance-free sludge handling, assuming the sludge is digested; and (3) ocean disposal permits flexibility in plant operation, assuming sludge is digested (17).

Ocean disposal of wastewater sludge is the most controversial problem of the day. The review of literature reveals that this probably is one of the most economical methods of ultimate sludge disposal. However, the long term environmental effects of this method have not been established. Middelton of EPA at Cincinnati, Ohio, viewed the ocean disposal of the sludge this way, "There are no hard and fast rules on this. It is the one major area of uncertainty. The ocean has a great capacity to receive discharges-- in some cases it might benefit from them, but the ocean should not be regarded as an infinite sink. However, it could be the receptor of brines and brackish streams. Clean, mixed salt stream should be accepted, but not DDT-laden stream or toxic sludges. We are primitive in our knowledge of pollution. Until we know more we should not side with one way or the other." (174)

The environmental effects of both barge and submarine disposal of sewage sludge have been studied by a number of investigators. A review of the investigations by Smith and Brown (160) reveal the following: (1) the sewage in large concentrations destroys the marine habitat in the immediate vacinity of the sludge field; (2) the sludge drifts slowly along the bottom because of currents; (3) coliform and related toxic substances are potential threats to shellfish within a radius of 5 to 10 miles of the site; (4) the toxic substance and coliform bacteria associated with the sludge are concentrated in bottom sediments; and (5) a great deal more field and laboratory work is required to accurately predict the detailed behavior of the sludge and the probable environmental response.

In summary, ocean disposal of sludge is the best economical disposal method for coastal cities and probably will be more attractive in the future as the volume of sludge increases due to growth of population; higher pollution control standards for water, air, and land; and continual increase in cost of the alternative methods. However, because of the observed adverse environmental effects of this method, indications are that the Federal Government may halt all ocean dumping in the near future.

Land Spreading of Liquid Sludge

Land spreading of liquid sewage sludge and sewage effluent has been practiced for centuries in Europe and Asia. It has also been used in the U.S., mostly in smaller communities where farm lands are located close to the wastewater treatment plants. Recently, many of the larger communities have also been seriously considering land spreading of sewage sludge as one of the most promising sludge disposal alternatives.

Land disposal of sewage sludge is generally characterized by application of liquid, treated (digested) sludge on crop lands in pre-determined rates and amounts. It is based on the "living filter" concept, letting nature recycle nutrients and water beneficially on land rather than detrimentally through streams and lakes (175). Land disposal could be used as an economical means of sludge treatment and disposal. If used as a means of sludge treatment and disposal rather than competition for chemical fertilizer, it becomes economically very attractive. In addition, liquid digested sludge contains soil conditioning agents and the elements essential to the growth of green plants. It has been reported (176) that some 20 or more elements are beneficial to plant growth and at least 16 are essential. All 16 elements and other nutrients and growth stimulators have been found in digested sludge. The fertilizer constituents of the sludge given in Table 16 indicate the sludge is not balanced fertilizer because of its low nitrogen, phosphorus, and potassium contents.

Heavy application of sludge may be a solution to this problem if provisions are made to control plant toxicity due to accumulation of toxic metals, such as copper, boron, lead, zinc, cadmium, etc. It is reported (164) that under normal loading conditions for ordinary sewage sludge it will take 50 years before accumulation of heavy metals reaches toxic levels. Metal toxicity can be controlled using lime to neutralize the acid soil, which then converts the soluble excess metal to an insoluble state. The metals then precipitate out and will no longer be available for the plant. If the metals are separated as hydroxides under high pH conditions, they will mineralize and be restored to their original condition in the soil (6).

The major factors effecting the economics of liquid sludge disposal are size (population), of the community; transportation costs; and land cost. Investigations of Riddle and Cormack on economics of liquid sewage sludge transport are reported in the literature (177). Figure 54 shows the relative costs of various transport alternatives for a city of 100,000. It appears that pipeline transport is most economical for distances ranging from 25 to 200 miles. Figures 55, 56 and 57 show comparative estimated costs of sludge disposal by alternative means for cities of 10,000, 100,000, and 1,000,000 respectively. It appears that for smaller cities land disposal is more economical where disposal sites are located within a 30 mile radius. For larger cities the economical distance for sludge disposal is increased to 100 miles.

Raynes (178) has compared the sludge disposal costs by filtration and incineration methods versus land disposal of liquid sludge using pipelines for cities ranging in population from 0.125 to 4 million. The effect of population on unit cost of sludge disposal resulting from this study is shown in Table 76.

TABLE 76

Effect of Population on Unit Cost of Sludge Disposal(178)

Populations in Millions	Incineration Cost ($ per dry ton)	Land Disposal Cost ($ per dry ton)
0.125	67	30
0.25	57	17
0.5	49	11
1	42	8
2	35	5
4	30	4

Figure 54

Cost of Transporting Sludge from City of 100,000 (177)

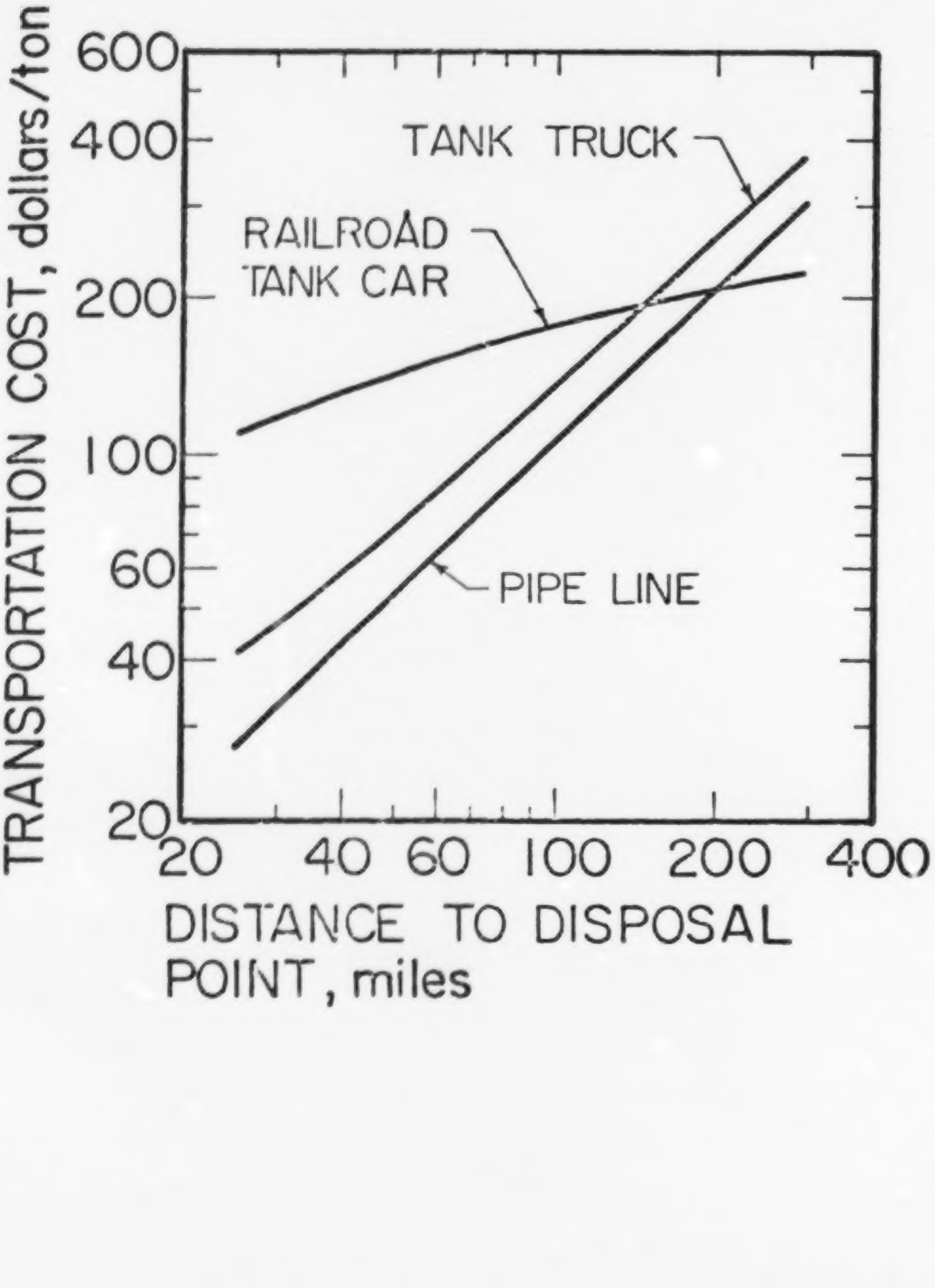


Figure 55

Cost of Sludge Disposal by Various Methods for City of 10,000 (177)

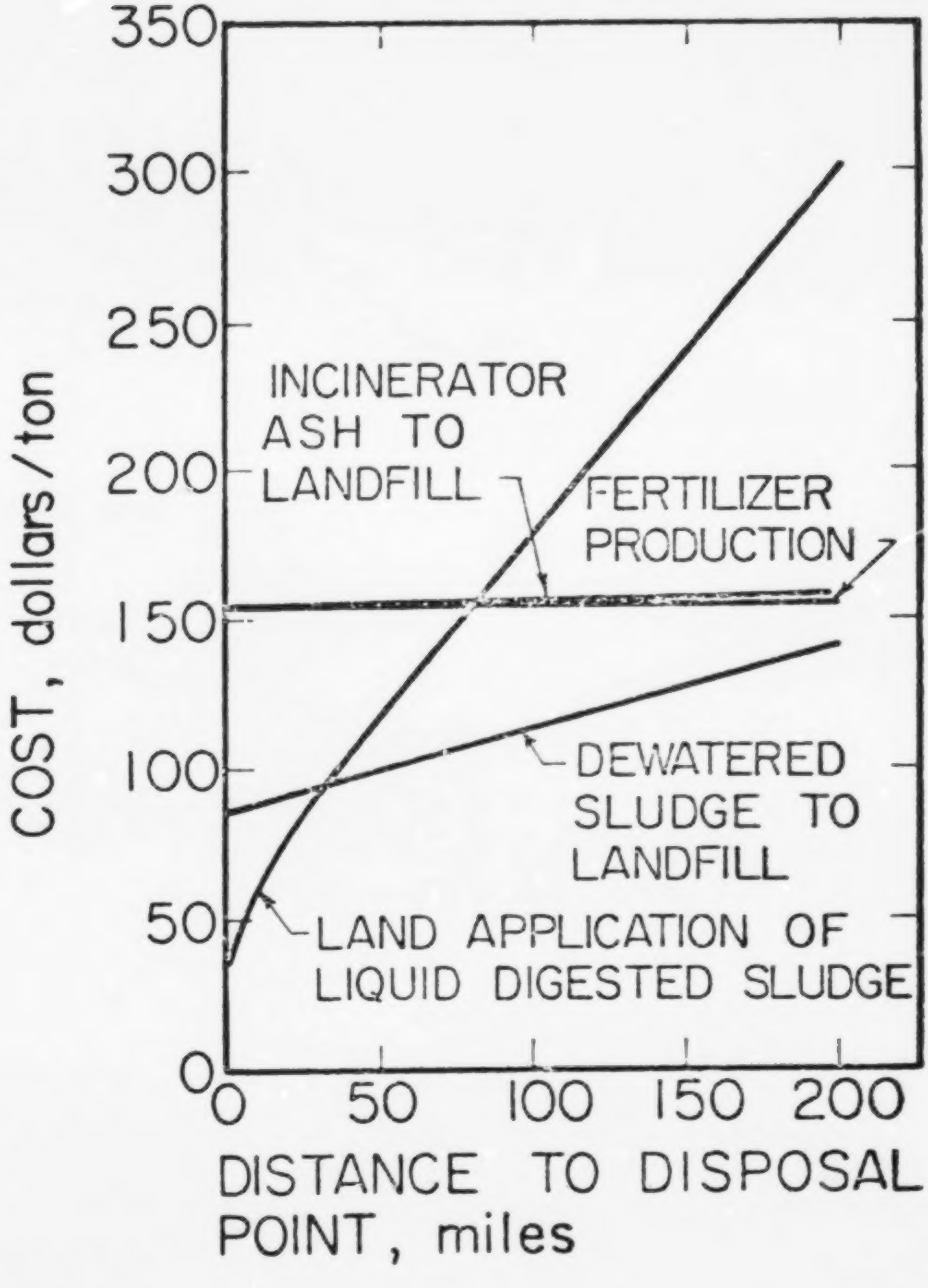


Figure 56

Cost of Sludge Disposal by Various Methods by City of 100,000[177]

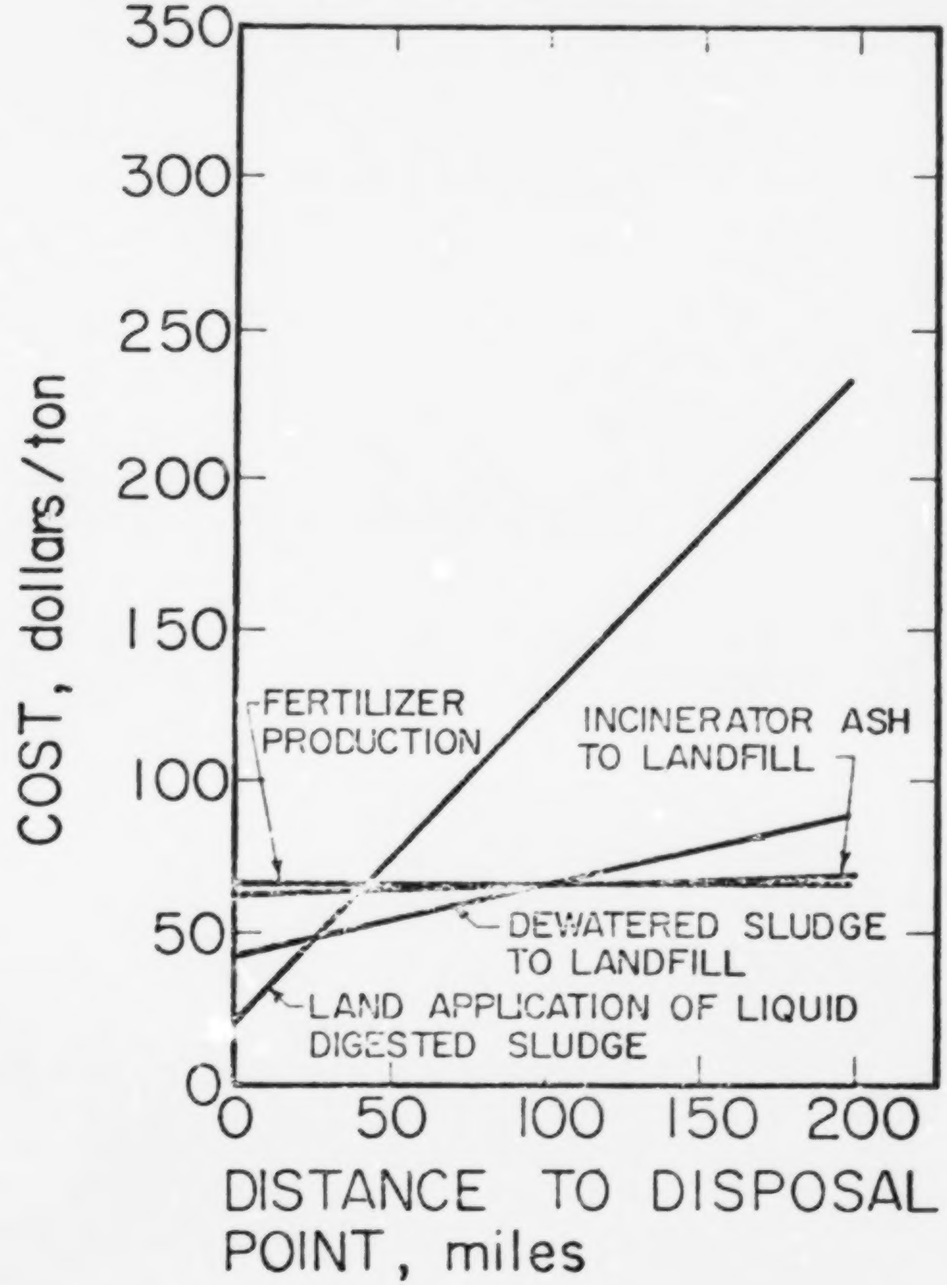
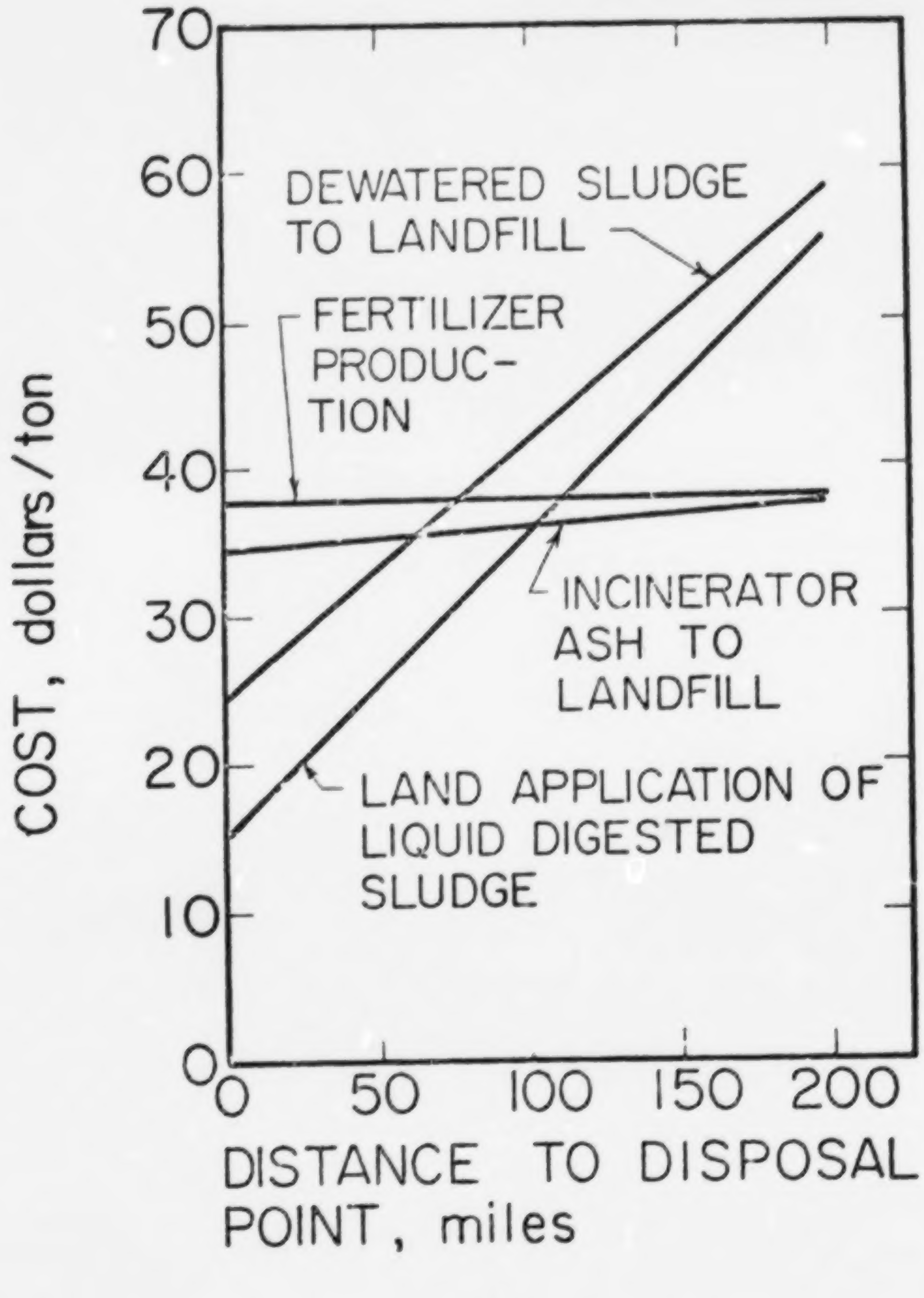


Figure 57

Cost of Sludge Disposal by Various Methods for City of 1,000,000(177)



Land is a cost item for treatment plants that buy or lease land. Land cost for small plants is not a factor since nearby farmland may be used. Some plants even receive a small payment for sludge that is spread on farmland.

Actual costs for land spreading of digested sludge compiled by Dotson, et al., (179) are shown in Table 77.

Public acceptance of liquid sludge disposal appears to have been the major problem for wide use of this method. There remains some uncertainty about the survival of various pathogenic organisms and viruses transmitted to soil from the application of the sludge, and their effects on surface and ground water. A review of the literature indicates that no serious incident of disease has been traced from sludge spreading on soils. However, this does not mean that application of liquid digested sludge on farmland is absolutely safe. More information is needed to confirm its safety. Disinfection may be needed where people come in contact with the sludge. Dotson, et al., (179), have suggested several methods for destroying pathogens in sludge. These include: (1) long term storage; (2) pasteurization at elevated temperatures (above 70°C) for 30 minutes or longer; (3) adding lime to raise the pH to at least 11.5 and holding pH at above 11.0 for two hours or longer; (4) disinfecting by high energy radiation, although costs are high; and (5) disinfecting with other chemicals, although the side effects are likewise unknown.

The rate of application of the sludge to soil depends upon such factors as soil type, climate, sludge characteristics, and the crop or land use. A typical application rate for a cornfield varies from 5 to 15 tons of solids per acre per year and for strip mines, up to 500 tons per acre per year are permissable.

In summary, it appears that land disposal of liquid digested sludge offers many advantages, including: (1) economy; (2) recycling of water, nutrients, and organic materials; (3) a final treatment process and ultimate disposal; and (4) nuisance-free if done properly. When compared with alternative methods, it has certain limitations, including possibilities of toxic metal accumulation, surface and ground water contamination and, to a lesser extent, health hazards and nuisance.

Land Reclamation

The successful disposal of wastewater sludge on land for land reclamation purposes has been practiced for centuries throughout the

TABLE 77

Summary of Costs for Land Spreading of Digested Sludge(179)

	Approximate plant size (mgd)	Estimated cost for land spreading of digested sludge (dollars per ton of solids)
New York, New York	--	$11.89
Chicago, Illinois	1300	26.02*
San Diego, California	90	10.57
St. Marys, Pennsylvania	1.3	19.92
Little Miami (Greene County, Ohio)	1.5	22.00
Piqua, Ohio	3.8	17.50 to 30.00
Franklin Regional Wastewater Treatment Plant, Franklin, Ohio	4.5	5.00
Montgomery County (Dayton), Ohio		18.00 to 21.00

*Expected costs after construction of pipeline. Present costs using barge transportation are $62.32.

world. Sewage sludge has been utilized to reclaim sandy soils and strip mine spoils by converting them into valuable crop land or recreation areas.

For several years New York City has used digested sewage sludge to build a topsoil for new parks. Marsh areas designated as park sites are first filled with garbage, then covered with two feet of sand, followed by a topping of the sludge cake. Sludge was applied at intervals until a 6-inch layer of dry sludge was built up. In 1967 the cost of sludge disposal in this method was about $7.50 per ton on a dry solids basis (17). This method was considered a suitable means for disposal of sludge.

The Golden Gate State Park in San Francisco consisting of 1013 acres was originally a sand dune. Sewage effluent was discharged to the sandy area for land reclamation purposes. In 1932 the irrigation was changed from sewage effluent to excess activated sludge. The land has been reclaimed and converted to a park area with dried digested sludge used as a fertilizer (180).

In 1956, the Division of Water Supply and Pollution Control, Department of HEW, experimented with the application of wastewater sludges to two strip mine sites in Stark County, Ohio. At one site 6 levels of terraces (18 ft. by 150 ft.) were constructed. Liquid sewage sludge was flooded into the benches ranging from 3 to 15 ga. per sq. ft. The second site was a high acid soil (pH 2.8 to 3.3), which had remained barren for about 8 years since exposure by strip mining. The sites were then seeded with grass after the sludge had been allowed to dry out. Results were extremely successful. It was concluded that the sludge apparently had acted as a germination aid, a provider of nutrients, and, to some extent, a neutralizer of acid-producing minerals in the soil. (180)

The largest land reclamation project of its kind has been proposed by the City of Cleveland, Ohio. It is proposed to transport sewage sludge to strip mine areas in Harrison County, located in the southeast part of the State of Ohio, through 97 miles of a 12 inch diameter pipe. The estimated cost of disposal including collection and transportation averages about $25 per ton of dry solids over a 28 year period (1972-2000), a savings of $5 to $15 per ton since some alternative methods are estimated to cost $30 to $40 per ton of dry solids (181).

Other land reclamation projects include the Metropolitan Sanitary District of Greater Chicago; Tucson, Arizona; Springfield, Illinois; Kaukake, Illinois; Las Vegas, Nevada; Miami, Florida; and San Diego, California; etc.

Investigations of health hazards associated with some of these sludge disposal projects have been made. Results of these investigations showed no adverse environmental effects. However, long term investigations may be required to confirm the results of these short term investigations.

In summary, it appears that this is a satisfactory method of sludge disposal to the extent that it does not cause pollution; it is relatively economical; and it utilizes the organic content of the sludge for beneficial uses.

Lagooning and Landfilling of Sewage Sludge

Lagooning of the wastewater sludge is a common method of sludge treatment and disposal. In municipal and industrial wastewater treatment plants lagoons are used for various purposes such as: (1) aerobic digestion of raw sludge; (2) thickening, storage and drying of digested sludge; and (3) permanent disposal of sludge or landfill.

Although lagooning of the sewage sludge has been a popular treatment and/or disposal method, because of its favorable economics, several disadvantages are insect breeding and nuisance, odor production, and ground water contamination.

Occasionally, dewatered sludge is discharged to landfill or a sanitary landfill area. In some instances the aim has been to reclaim the land for parks, playgrounds, etc. The cost of sludge disposal by landfill is obviously more than lagooning, however, disadvantages are practically the same as those for lagoons.

Sludge disposal by lagooning and landfilling is relatively common at the present time, particularly in smaller communities due to its favorable economics, flexibility and simplicity of operation. However, strengthening of pollution standards, the unavailability of land in the vicinity of treatment plants, and the adverse environmental effects will probably decrease its popularity and use.

Disposal of Dried Sludge as Fertilizer or Soil Conditioner

Disposal of dried wastewater sludge on land as fertilizer or soil conditioner has been practiced very extensively in Europe and Asia. Table 16 shows the fertilizer content of the sludge. It appears that sludge is not a competitor of the chemical commercial fertilizer because of its lower nitrogen, phosphorous, and potash contents. However, sludge contains a number of trace elements essential to plant growth that are not found in chemical fertilizers.

The fertilizer value of a sludge depends on the sources of wastewater and the type of treatment processes to which both wastewater and sludge are subjected. Sludge produced from treatment of pure domestic wastewater has a higher fertilizer value as compared with sludge obtained from combined domestic and industrial wastewater. Sludge resulting from an activated sludge process contains 40 to 50% more nitrogen and phosphorus than sludge resulting from an anaerobic digester.

The application of raw sewage sludge on land involves potential health hazards. Furthermore, its physical structure and high grease content is believed to have a detrimental effect on the soil structure and growing plants (182). For these reasons sludge is generally treated and dried on sand beds; mechanically dewatered; or dried by artificial heat prior to disposal on land.

The review of literature reveals that much field and greenhouse evaluation of wastewater sludge has been investigated. In general, application rates ranging from 10 to 40 tons per acre have been recommended. Higher application rates are not recommended because of possible toxicity due to the trace element build-up in the soil. Liming of the sludge prior to dewatering or liming of the soil receiving the sludge fertilizer has been found to have advantages which are: (1) neutralizes excess acidity of the soil and precipitates some metals; (2) encourages bacterial decomposition of organic solids, hence, increasing the effectiveness of sewage sludge; (3) makes phosphorus more available; and (4) improves the physical structure of heavy soils and supplies a necessary element, calcium (182).

In general, the sludge fertilizer market has not been a profitable one. Many treatment plants with heat drying equipment have changed from fertilizer production to sludge incineration or landfilling. However, several wastewater treatment plants, such as those in Milwaukee, Chicago, and Houston, have been very successful in marketing dry activated sludge. Burd (17) has reported that over 200,000 tons of sludge fertilizer were solid annually at prices ranging from $12 to $18 per ton by Milwaukee, Chicago, and Houston. Cost of sludge disposal by this method for Chicago reaches approximately $45 per ton of dried solids.

In summary, sludge disposal as a fertilizer or soil conditioner deserves much more consideration. Most obstacles to date have been the lack of a profitable market. However, it should be noted that dried sludge which may be used as fertilizer or soil conditioner is a significant and potential ultimate disposal method. The profit gained from the sale of dried sludge should not be emphasized since it is not significant, but the demand for sludge utilization is great today. It can effectively be used as fertilizer for parks and individual lawns, and as a supplement or filler for chemical fertilizer.

Underground Disposal

Disposal of well treated wastewater sludge in subsurface strata that contains natural and man-made cavities, such as depleted mines, wells, and caves has been reported by many investigators (17,183, 184). They have believed that subsurface disposal is competitive with other disposal methods economically. However, several problems involved with this method of disposal, include: (1) high solids content of the sludge; (2) legislative policies in many states prohibiting this method of disposal; (3) difficulty finding a proper site; (4) high cost of excavating underground sites; and (5) possibility of permanent ground water contamination if the sludge should leach into the water supplies.

Deep well injection of sludge has been practiced by Dow Chemical Company for disposal of waste activated sludge at one of their largest production facilities. It was noted that the economics of sludge disposal was greatly improved using deep-well injection; however, cost values are not available (184).

Deep-well injection of industrial sludges has been practiced quite often, particularly for plating and radioactive wastes. In these cases the sites are studied very carefully and all measures are taken to prevent leaching.

By-Product Recovery

Non-fertilizer by-product recovery of sewage sludge has been studied by many investigators. It appears possible to recover several by-products.

The recovery of Vitamin B-12 from wastewater sludge has been discussed by Hoover (185) and Leary (186) as a supplement to animal feeds. Vitamin B-12 was successfully recovered from dried undigested activated sludge in pilot plant studies in Milwaukee. It is believed that Vitamin B-12 is derived from raw sludge and, in part, from biological synthesis in the activated sludge aeration tanks. The pilot plant studies indicated that 308 pounds of pure Vitamin B-12 could be produced from the Milwaukee 70,000 ton per year sludge production.

The Metropolitan Sanitary District of Greater Chicago, in cooperation with the University of Illinois, has investigated the value of heat dried activated sludge as an additive to animal feed. Feeding tests have indicated that activated sludge at levels of 0.5% to 2% is a satisfactory source of Vitamin B-12 for pigs and chickens (42).

Rudolfs (187) has reported that for a wastewater sludge which runs high in grease content and low in alkalinity, successful extraction of grease from raw sludge solids was made using the process known as "Miles Acid Process."

Thompson, et al (8), have discussed the possibilities for commercial recovery of some of the metals found in the sludge. The amount of metals that could be recovered from the Oklahoma City Southside Treatment Plant producing 2 million pounds of air dried sludge in 1962 were estimated. It was noted that, assuming 100% recovery, 940 lbs. of silver, 5640 lbs. of copper, and 11,750 lbs. of titanium could be recovered annually.

Beeckman and Ng (171) have reported on prospects for pyrolyzing sludge to obtain an absorbent with greater capacity than the fly ash produced by sludge incineration. (A complete discussion of this method and results obtained can be found in the previous chapter, under sludge pyrolysis.)

Feasibility of hydrolysis of sludge using low pressure steam with SO_2 as a hydrolytic adjunct and utilization of the resulting hydrolysate was reported in the literature (188). Sulfurous acid, when used as a hydrolytic adjunct in the treatment of activated sludge under hydrolytic parameters of the sludge at $140^{\circ}C$ for one hour, increased the solubility of the solids by 20%. Concentration of the solubilized extract produced a molasses-type syrup; 85% of the solids content of the syrup was organic; over 20% of these solids were proteinaceous material. Rat feeding studies showed that it could be used as animal feed.

In summary, it appears that by-product recovery is possible from municipal sludges. However, marketing and the value of product and associated marketing problems have not been worked out. In general, the market place determines the by-product specifications, and, in most cases, these specifications are rigid, involving product purity and concentration. A great amount of development and additional research needs to be done before this appears to be practical.

WATER TREATMENT PLANT SLUDGE DISPOSAL AND/OR UTILIZATION

In 1946, the American Water Works Association appointed a commitee to survey and study the disposal of wastes from water supply treatment plants. After six years of study a comprehensive report was prepared. It was then noted that more than 96% of the 1530 reporting plants discharged sludge to the nearby watercourse or lakes without treatment and only 3% used drying beds.

In 1968 a questionnaire survey of the 100 largest cities in the U.S. was conducted by Washington Aqueduct Division to identify the method of filter wash water and of sludge disposal used (190). This survey indicated that basin sludge and filter washwater were still discharged into surface waters. Only a small percentage of the plants used lagoons and landfills. Filterwash waste, however, was noted to be better controlled, 21% lagooned washwater and 18% returned to the rapid mix.

Prior to 1968 no restrictions were imposed on discharge of these sludges to streams and lakes. It was then that action was taken by the FWPCA (now USEPA) to implement the Water Quality Act of 1965 and passage of stricter state laws to regulate disposal of these wastes.

It appears that an intensified effort is in progress by the water industry, namely, American Water Works Association, to put the task of handling and disposal of these wastes in proper perspective.

Methods for disposal and utilization of these wastes that are presently used are listed in Table 75. These methods shall be discussed briefly in the following sections.

Direct Discharge to Streams, Lakes, and Ocean

Discharge of the sludge without treatment to nearby available water is economical and simple. These have been the main reasons for its popularity. However, the recent survey made by the AWWA Research Foundation (52), has indicated that this method is no longer accepted. Federal and State water laws have totally eliminated direct discharge of these wastes into surface waters. At the present time most municipalities have already been converted to other means of disposal, or are in the process of doing so.

Direct disposal of sludge from water treatment plants into surface waters may not cause serious health hazards as compared with wastewater and wastewater sludge, because of its low organic content. However, the high solids content of these sludges may color the receiving water, increase its turbidity, and may settle and form a sludge blanket interferring with the natural aquatic life cycle.

Lagooning of the Sludge

Lagoons can serve as settling basins or sludge thickeners preceding some other process (temporary lagoons), or can be used for final disposal of sludge (permanent lagoons). Lagooning of sludge is a relatively simple and inexpensive sludge disposal method. Land requirements are large, but operating costs are generally low. Problems associated with lagoon disposal of the sludge are land availability in the vicinity of the plant and occasionally odors. Lagooning of softening basin sludge is practically odor-free, due to the high pH of the sludge which prevents biological activities. On the other hand, lagooning of purification wastes does involve odor and nuisance because of the higher organic content and biological population.

Parameters given for design and operation of permanent lagoons are shown in Table 78 (55).

Lagoons should be considered for small treatment plants, where land is inexpensive. However, investigation of the sludge toxicity and metal concentration must be made so that ground water contamination is prevented. After the lagoon is filled it could be reclaimed as useful land through application of an earth cover.

Agricultural Utilization

Disposal of softening sludge on farm land has been frequently practiced, particularly in smaller communities. Lime sludge from softening plants has been reported to be as effective as the agricultural limestone from the quarries used for improving soils. Lime sludge's total neutralizing power ranges from 92 to 100% as compared with 60 to 90% for commercial lime used in soil (55). Furthermore, lime sludge particles are much finer than those of marketed lime. Advantages of the finer particles are that they react faster and more completely with the acid in the soil.

Lime sludge can be applied on farm land both in liquid (1 to 5% solids) or dewatered (20 to 40% solids) states. An application rate of 3 tons

TABLE 78

Design Criteria and Operational Guides for Lagoons(55)

	Thickening and Storage Lagoons	Permanent Lagoons
Number of subdivisions in lagoon	At least 3, preferably 6	At least 6
Depth (feet)	5-10	5-10
Fill time (years)	$2\frac{1}{2}$	20
Area (Acres/MGD/100 mg/l hardness removed)*	0.7***	2.0
Decanting Mechanism	Stop plate outlet or telescope valve	
Bottom Slope	0.5% to 1.0% away from the inlets	
Embankment Slope		
Exterior Side	3:1	
Interior Side	2.5:1	
Depth of Applied Wet Sludge (inches)	Up to 12	Equal to or less than 2
Final Solids Content (%)	25-40	Equal to or more than 70
Volume Reduction (%)	80-90	95**
Sludge Distribution System	Piping and valving arranged (1) to allow uniform distribution, (2) so that flow distance in the bed is less than 200', and (3) so that distance between the sludge inlet and the decanting device is 100' or greater to avoid short circuiting.	

* Based on lagoon depth of five feet

** After compaction

*** Based on 85% volume reduction

per acre per year has been recommended for Ohio soils (55).

Disposal of lime sludge on farm land appears to be an advantageous disposal method. However, sludge must be analyzed for toxic metal content prior to land application.

Discharge to Sewers

Disposal of sludge to both sanitary and storm sewers has been practiced. Discharge to storm sewers is no longer acceptable for reasons given previously. Discharge of lime sludge from softening plants into the sanitary sewers has increased very rapidly. Krasauskas (191) reported that lime sludge disposal to sanitary sewers has increased from 0.3% of the water treatment plants surveyed in 1953 to 8.3% in 1968.

A recently developed use of lime indicates that lime sludge may be used in sewage treatment plants for wastewater sludge stabilization. No adverse effects of lime sludge disposal into sanitary sewers has been reported in the literature studied. However, it could cause problems, including: (1) precipitation if flow velocity is below 2.5 ft. per second, or solids formation on walls of sewers, reducing the hydraulic efficiency of the pipes; (2) in excess amounts it may hamper the biological activities of the secondary treatment process in the wastewater treatment plant; (3) in excess amounts it may reduce the digester efficiency by increasing solids content and by increasing the hydraulic loading of the digester; and (4) it may reduce the efficiency of the secondary digester by increasing the sludge density.

Disposal in Sanitary Landfill

Disposal of water treatment plant sludge in sanitary landfills appears to have a number of advantages. Mixing of the sludge with refuse could help the compaction of refuse in a landfill. Leaching has been reported when liquid sludge was applied, but leaching could be controlled if dewatered sludge is used. The precent of sludge that can be absorbed in a landfill without producing a leachant is given in Table 79.

Application of Sludge to Strip Mine Spoils

Sludge from softening plants can be utilized at strip mine spoils for land reclamation purposes. Lime sludge will obviously reduce the acid drainage and will aid in reclaiming the acid bearing soils.

TABLE 79

Percent of Sludge Produced That Can Be Absorbed in Landfill(55)

Percent Solids in Sludge	Percent of Sludge Produced Absorbed in Landfill Without Leaching*
4	16
10	45
20	100

* Based on (1) 1600 pounds refuse per capita per year, (2) 100 gallons per capita per day water usage, (3) removal of 100 milligrams per liter hardness, (4) absorption of 65 gallons of water per ton refuse, (5) nine feet depth of fill, (6) density of refuse is 13 pounds per cubic foot.

Application rates are not available, however, it is believed that vast amounts of sludge can be absorbed by the strip mine areas. Cost of the sludge transportation is generally the main problem, but increase in the value of the reclaimed properties could justify this cost.

By-Product Recovery

By-product recovery of the waste from water treatment plants includes lime recovery, magnesium carbonate recovery, and alum recovery. The production of lime from softening plant sludge has almost eliminated the disposal problem. Recalcination has practiced in large cities in the U.S., including Dayton, Ohio; Miami, Florida; and Lansing, Michigan. Recalcination is not only the best ultimate method, it could also be profitable by selling the excess lime produced. Dayton has reported a profit of $0.79 per ton of lime produced, while Miami has reported this profit to be $5.08 per ton of lime produced. In the recalcination process vast quantities of CO_2 are also produced from the burning of fuel and conversion of $CaCO_3$ to CaO. Carbon dioxide has been recovered and used (in Dayton) in the recarbonation chamber to dissolve the $Mg(OH)_2$ present in the sludge and subsequently precipitated from the $CaCO_3$ sludge.

Lime recovery, although it is a profitable and most efficient method of sludge disposal, is generally limited to large plants. Capital and operating costs become prohibitive as units get smaller.

Magnesium carbonate recovery is generally associated with lime recovery. There are two possible methods for recovering magnesium values, as $Mg(OH)_2$, by selective softening, or as $MgCO_3$ from the carbonated lime sludges. Selective softening is not practical primarily because it would require major changes in the plant and complicate the softening operation (192).

Recovery of magnesium greatly enhances the quality of lime produced. Carbonation of the softening sludge containing appreciable magnesium hydroxide can dissolve the insoluble magnesium salt. The soluble magnesium carbonate can be physically separated from the calcium carbon precipitate. The utility of magnesium carbonate as a purification plant coagulant to replace alum is being evaluated at Montgomery, Alabama (52).

Aluminum sulphate coagulant has been recovered from the purification wastes containing appreciable amounts of aluminum in both Japan and France. Aluminum hydroxide wastes resulting from purification plants are basic in nature. Acidification of such wastes produces a soluble reuseable coagulant and inert material.

Although this process substantially reduces the volume of sludge for final disposal, success of this method depends upon the efficiency of separation of the recovered alum solution from the inert material not affected by acidification; and also upon the minimizing of impurities, such as the iron and manganese buildup in the recovered solution.

ECONOMICS OF WASTEWATER SLUDGE DISPOSAL

It is apparent that there are many factors effecting the economics of wastewater sludge disposal and utilization. These factors include: plant location; type of treatment processes to which both wastewater and the sludge are subjected; amount, nature and ultimate disposal of the wastes; air, water and land pollution standards and requirements; the availability of land and transportation; the cost of construction, operation, and maintenance of the necessary facilities; and the availability of a market place for the sale of by-products.

Numerous papers (11, 17, 156, 160, 167, 172, 179, 180, 193, 194, 195, 196, 197, 198) have discussed the economics of sludge disposal and utilization. It is interesting to note that almost every author admitted, directly or indirectly, that sewage sludge is a liability in any sewage treatment plant, despite the fact that it has some fuel and fertilizer value. This general opinion is based upon the fact that the benefit-cost ratio almost always falls below unity. Also, the aesthetic and environmental benefits derived from a specific disposal method are not considered in the benefit-cost analysis.

Due to the fact that numerous factors effect the economics of sludge disposal, it is not feasible to establish a general sludge disposal and utilization guideline applicable to every treatment plant. In Table 79 is presented the range of sewage sludge disposal costs compiled from various literature sources. These values give only an order of magnitude, but are useful as general information. Further, in Table 79 it is suggested that selection of the wastewater sludge disposal method for a particular plant requires a complete economic analysis of all available methods.

TABLE 79

Sludge Disposal and Utilization Costs

	Raw Capital and Operating Costs ($ / Dry Ton)	
	Range	Average
1. Barging to Sea	5 - 25	9
2. Pipeline to Sea	--	11
3. Liquid Sludge Disposal on Farmland	5 - 40	15
4. Liquid Sludge Disposal to Strip Mines	16 - 25	20
5. Landfilling Dewatered Sludge	10 - 50	25
6. Heat Drying and Selling as Soil Conditioner or Fertilizer	25 - 60	40
7. Lagooning	8 - 25	12
8. Wet Air Oxidation	40 - 50	45
9. Incineration	25 - 70	50

Sludge disposal and utilization methods currently being practiced can be divided into three major groups. Group I includes disposal and/or utilization of liquid digested sludge in the sea, or on land. Ocean disposal of liquid sewage sludge by barges or through submarine outfalls is practiced by many coastal cities. The reported costs for New York and Philadelphia (160,167) are about $9/ton of dried solids for barging the liquid sludge to the disposal sites. Although ocean disposal of sewage sludge is economically very attractive, ecologically it is not a satisfactory method.

Disposal of liquid digested sludge on farmland, and for reclamation of strip mine spoils and sandy soils appears to be the most advantageous disposal and utilization method. It satisfies both economical and ecological constraints. This method is definitely an ideal disposal method for smaller communities (20,000 or less), where farmlands are located in the proximity of the sewage treatment facilities. It is also economically feasible for medium and large size communities, where receiving lands or strip mine spoils are located within a reasonable distance.

Extensive studies have been made on the transportation of liquid digested sludge. Results of the study made by Riddell and Cormack (200) are shown in Figures 54, and 58 thru 61. It appears that truck transportation is most economical for small communities (10,000 pop.) for distances up to about 150 miles. Furthermore, use of pipeline transportation does not become economical for a distance of 25 miles until the population reaches 150,000. (The cost of pipeline transportation has been based on a minimum pipe diameter of 6 in., a maximum pumping head of 220 ft., and a sludge solids concentration of 3.5%).

The Metropolitan Sanitary District of Greater Chicago conducted extensive research to determine the best possible method for disposal of their sewage sludge. Results of this study (shown in Figure 62) indicated that application of digested liquid sludge on land for land reclamation purposes was not only the most economical disposal method, it also was compatible with environmental standards and requirements; it conserved organic matter for beneficial use; and it did not adversely effect the water treatment cycle.

Raynes (193) in conjunction with a land reclamation project for the United States Public Health Service has made an economic analysis of pipeline transportation of digested liquid sludge. Results of the costs, population, and distance are shown in Figure 63. The sludge

Figure 58

Transportation Cost

Population 10,000[199]

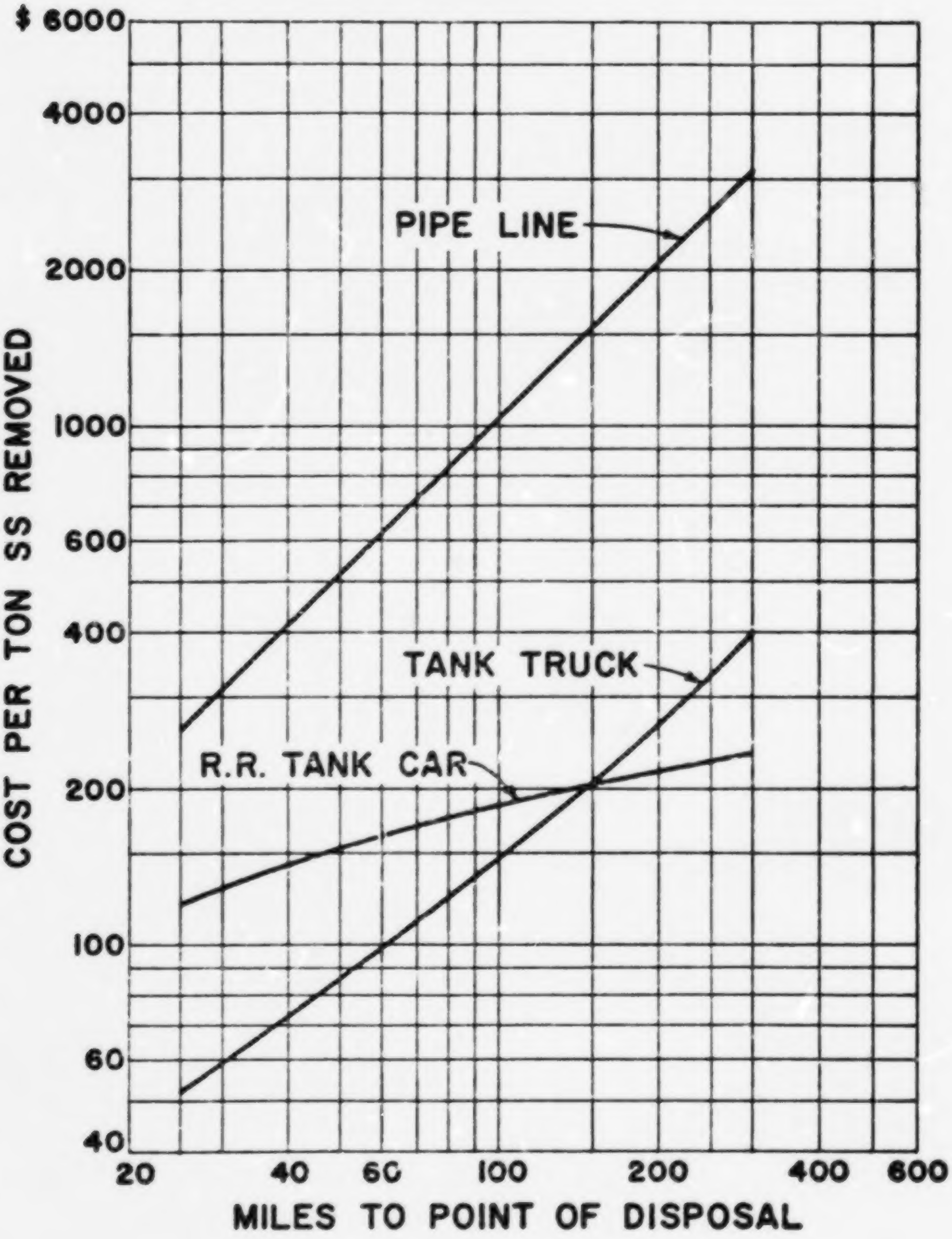


Figure 59

Transportation Cost

Population 1,000,000[199]

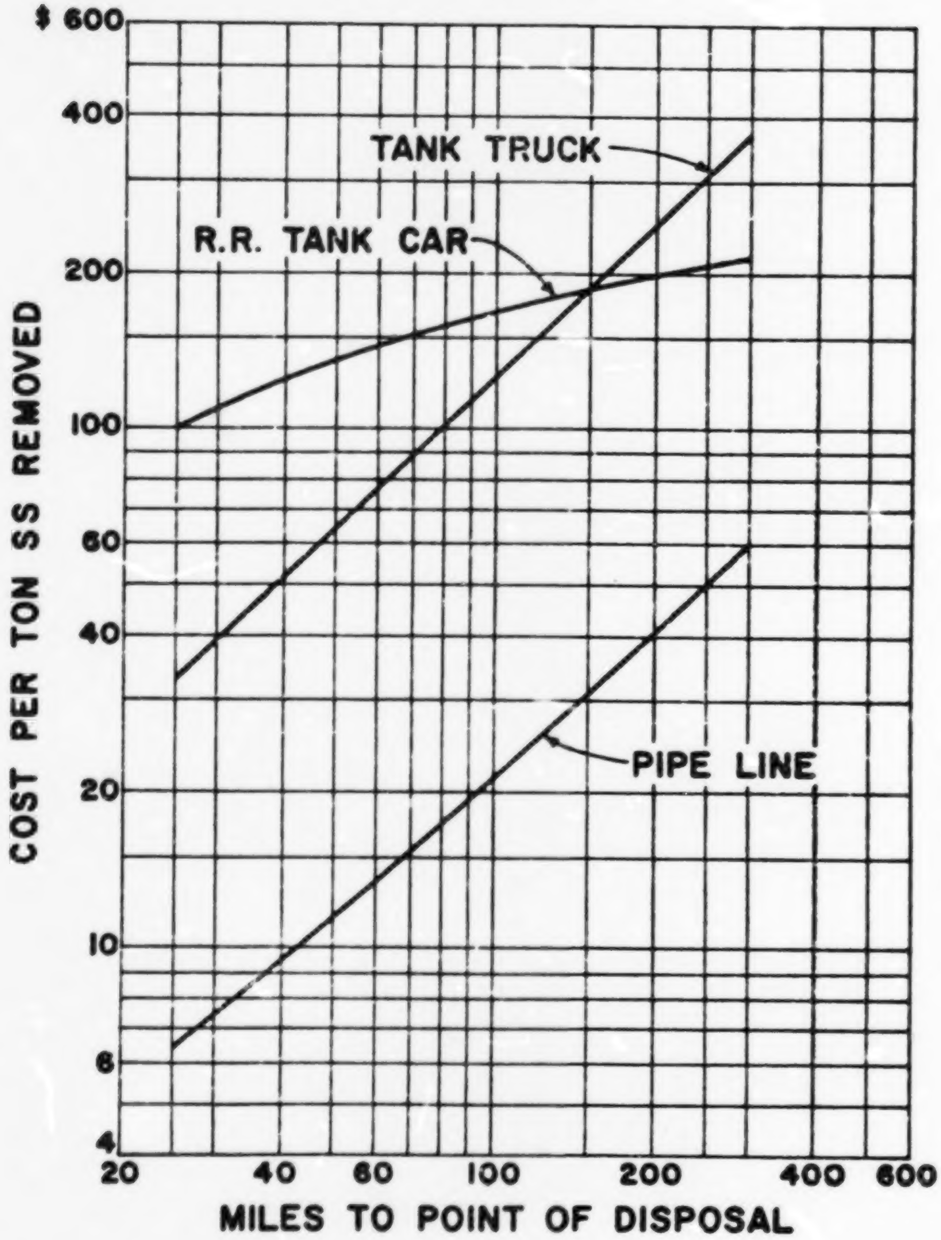


Figure 60

Transportation Cost

25 Miles(199)

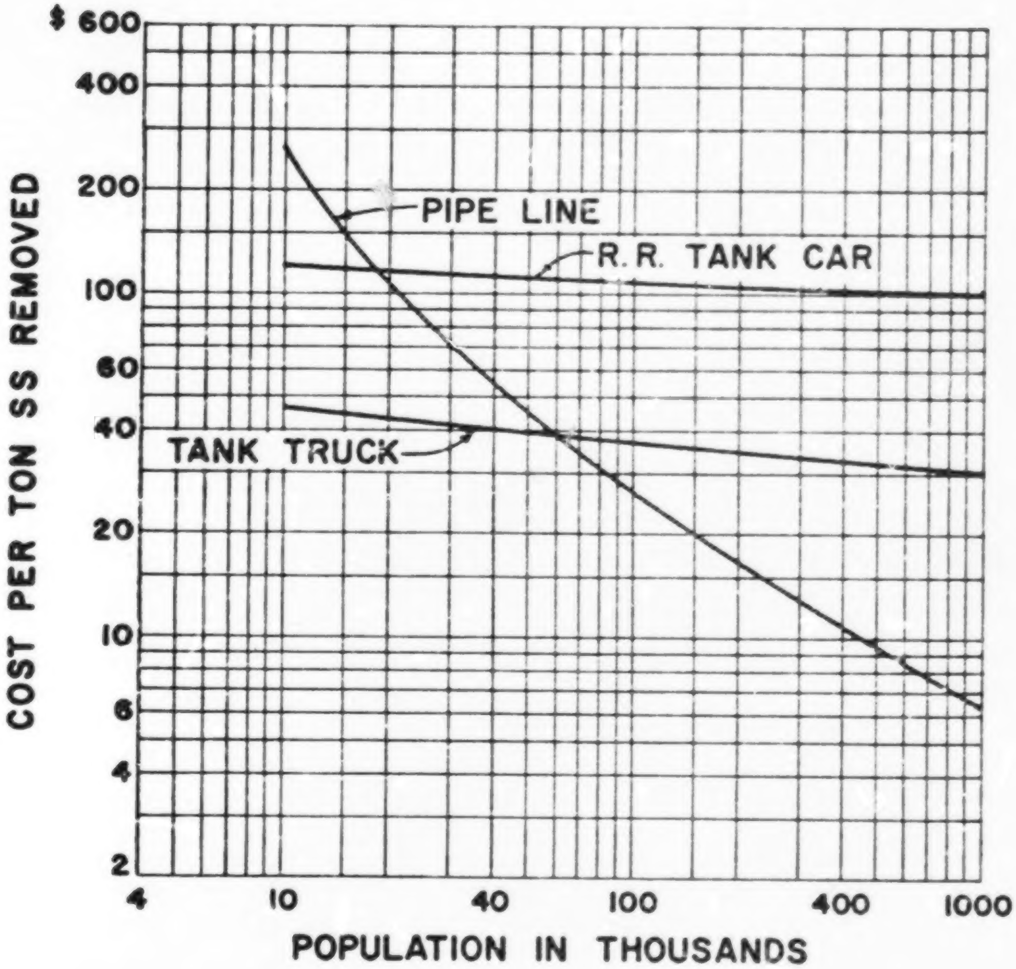


Figure 61

Transportation Cost

300 Miles[(199)]

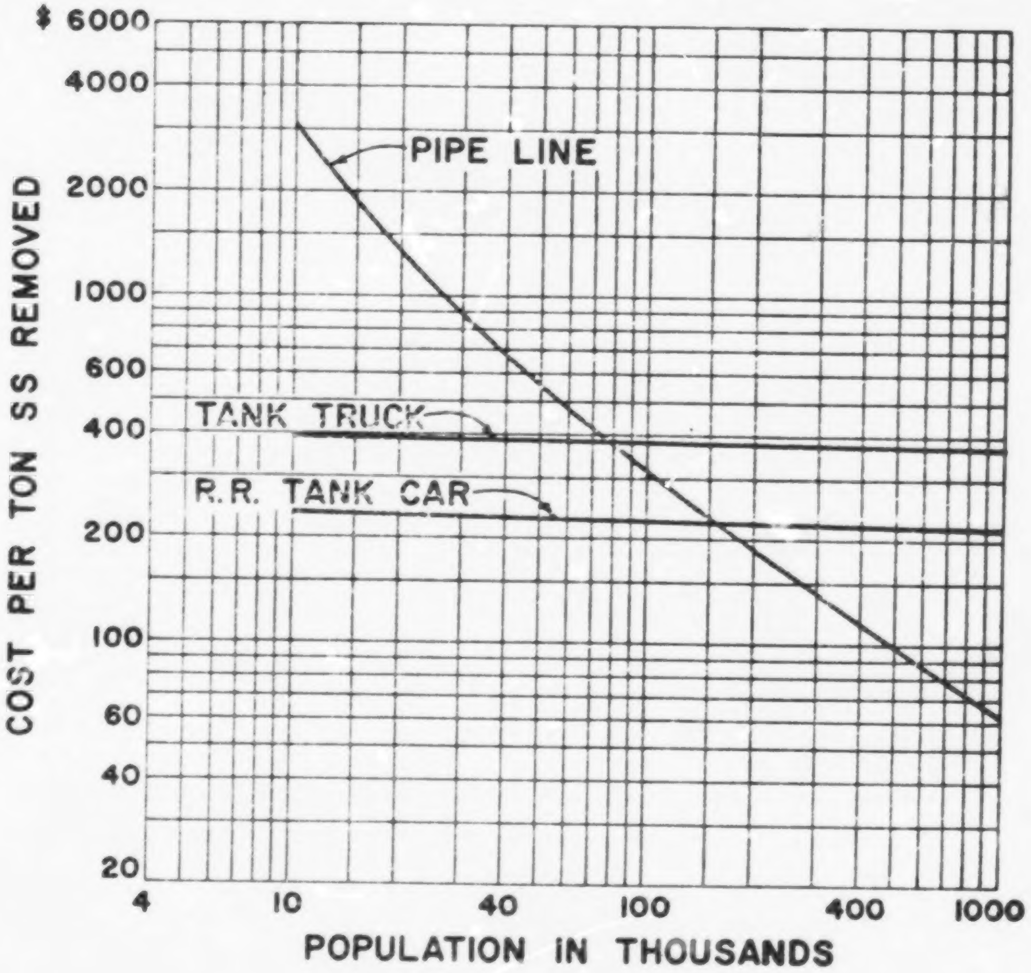


Figure 62

Costs of Disposal Methods for Activated Sludge(180)

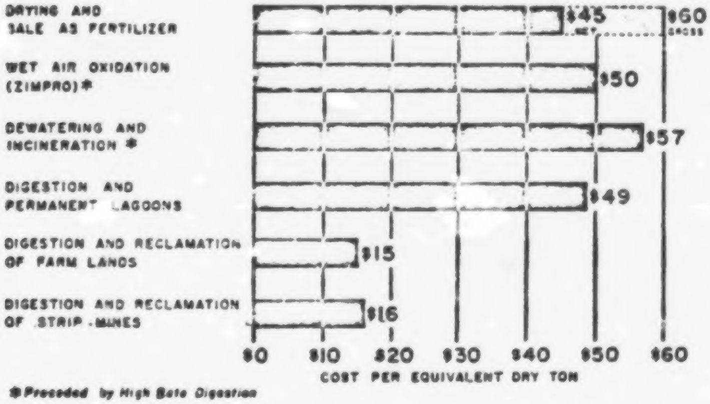
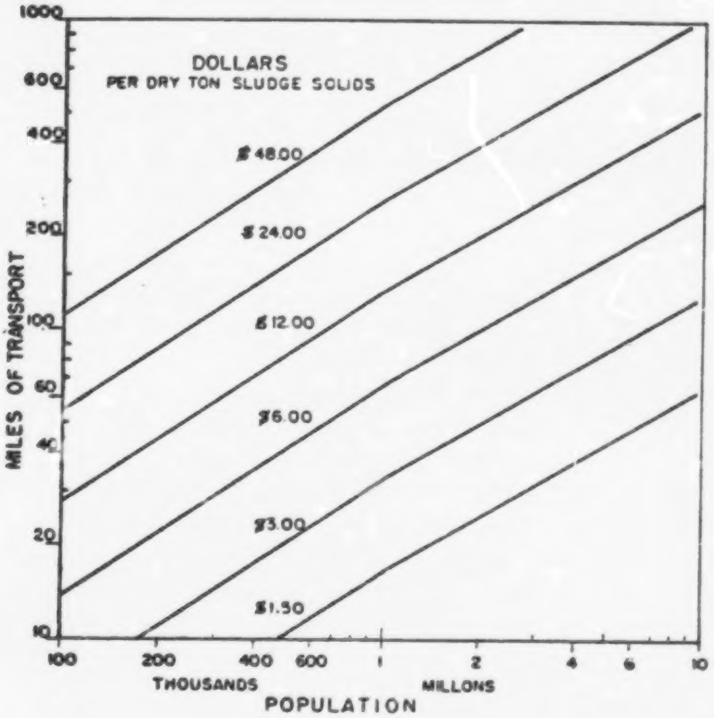


Figure 63

Pipeline transportation costs per dry ton sludge solids(193)

($/ton ÷ 0.9 = $/metric ton; miles X 1.6 = km.)



used for this analysis was assumed to have a solids concentration of 5%.

Group II includes disposal and utilization of dewatered or dried sewage sludge on farm land as soil conditioner or fertilizer. Sludge dewatering on sand drying beds and the application of the dried sludge on farmland have been shown to be both economically and ecologically acceptable. Land availability and land costs in large urban centers make this method economically unattractive; however, for small and medium size communities, it should be given serious consideration when a sludge disposal method is to be selected.

Multiple hearths, fluidized beds, and similar devices have been employed for sludge drying purposes. The cost of sludge drying by such devices is generally high, as opposed to complete combustion (incineration) of the sludge. However, the return money from the sale of the dried by-products may drastically reduce the net cost of ultimate sludge disposal when compared with complete incineration. Marketing and the local market potential for the dried sludge appear to be the main problems. An extensive study was made by Quirk (200), comparing the economic costs of wastewater sludge incineration vs. sludge drying. Two different systems were studied. These systems included: (1) only incineration equipment, and (2) a dual purpose system, with incineration or drying equipment. Results of the annual unit costs are presented in Table 80. It is readily seen that the cost of drying is far greater than that of incineration. Furthermore, the cost of deodorizing dried sludge is quite substantial.

Figure 64 illustrates the results of an analytical technique using unit costs presented in Table 80. It presents a picture of the effect of fluctuating market conditions on the relative economy of incineration versus incineration/drying. The loss area indicates that net total annual costs of an incineration/drying cycle are greater than those associated with a simple incineration operation. The relative economy area indicates that net total annual costs for incineration/drying are lower in that area than those associated with simple incineration operation. The profit area indicates that the product income is exceeding the annual costs. Figure 65 represents actual costs rather than cost ratios. The solid curves assume a non-deodorizing cycle, where the dashed curves are based on deodorizing to at least 1200°F. The cross-hatched area represents the range in soil conditioner selling price which can normally be anticipated. Analysis of this figure

TABLE 80

Unit Cost Summary[(200)]

Equipment	Operation	Cycle	Cost/Ton D. C. S. Incineration $	Vacuum Filtration $	Total
1. Incineration	Incineration	Deodor.	18.97	10.51	29.48
"	"	Non-Deodor.	15.51	10.51	26.02
2. Incin. -Drying	"	Deodor.	21.94	10.51	32.45
" "	"	Non-Deodor.	18.19	10.51	28.70
3. " "	Drying	Deodor.	37.02	10.51	47.53
" "	"	Non-Deodor.	20.09	10.51	30.60

Figure 64

Comparative Economy of Incineration vs. Incineration-Drying Based on a Flash-Drying System; Vacuum Filtration Excluded (200)

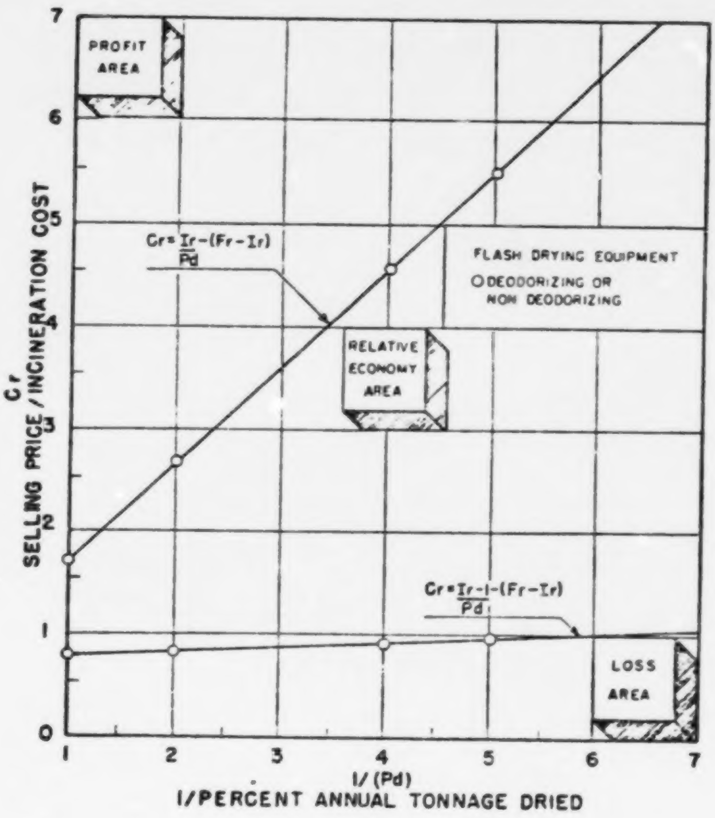
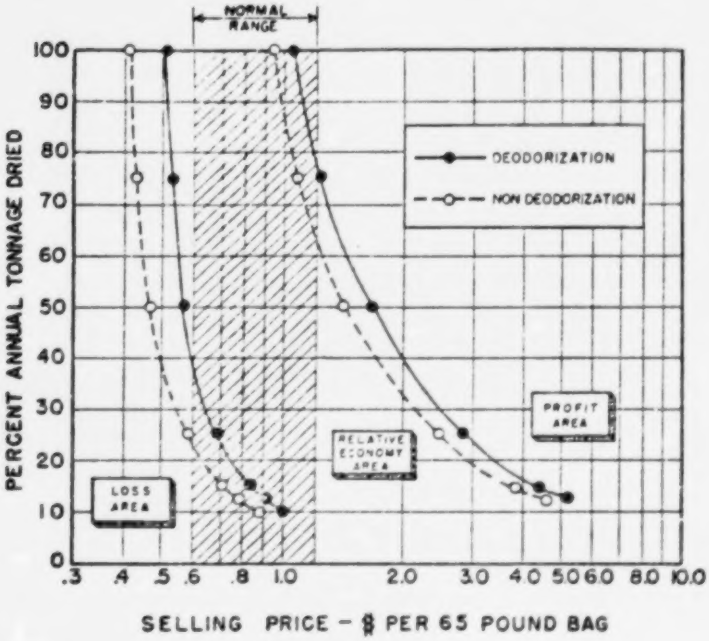


Figure 65

Comparative Economy Curves for Incineration-Drying



indicates the following: (1) at an average selling price, full cost recovery is not possible; (2) under the most favorable market conditions, from 60 to 80% of annual production must be sold to recover the total annual cost of the incineration/drying operation; (3) under the least favorable market conditions, from 25 to 40% of the annual production must be sold in order to obtain relative economy; and (4) deodorization requirement exerts a significant influence on the market conditions required to justify an incineration/drying operation.

Group III includes sludge incineration. It is apparent that this is the most expensive method of all. Furthermore, application of this method does not allow recycling of the valuable organic matter back to nature, and the resulting incinerator ash imposes additional disposal costs. Table 81 presents approximate costs of various types of incinerators. Table 82 presents the capital outlay required for incinerator systems by population group. Sludge incineration costs are affected by many factors (156), including: (1) nature of the wastewater sludge; (2) sludge conditioning method and the amount and type of chemicals used; (3) size and design of incinerator system; (4) costs of utilities (fuel, power, water); and (5) air pollution control facilities required. The economics of sludge incineration were also studied by Raynes (193). Results are presented in Table 83.

An extensive study of the ultimate disposal of sewage sludge from 23 treatment plants in Montgomery County, Ohio, was made by Seifert (201). This study was based on a regional sludge disposal concept. The study proposed ten alternatives for sludge disposal and utilization. A detailed cost analysis of the methods under consideration was made. Based on their technical and economic feasibility the alternatives were then compared. Table 84 presents the various disposal systems studied, their costs and ranking. Results of the study showed that pipeline transport of the liquid digested sludge to 640 acres of farmland was the most economically viable disposal method.

The reviews of literature indicate that the costs of disposal of sludge from water treatment plants are not clearly reported or recorded. Furthermore, the type of sludge, the processes employed prior to disposal, and the type of disposal method will greatly influence the disposal cost. It appears that each sludge disposal method is unique; consequently, the costs are variable. In general, sludge disposal costs amount to about 5% of the total cost of treating water. In some softening plants where recal-

TABLE 81

Pricing Information on Incineration Systems(156)

Type	Manufacturer	Size (lb/hr)	1968 Dollars	
Fluid Solid	Dorr-Oliver	200	180,000	
		400	300,000	
		1,000	550,000	
		2,000	825,000	
Multiple Hearth	Nichols	500	300,000	
	Bartlett-Snow-Pacific	2,000	550,000	
		4,000	700,000	
		6,000	850,000	
Cyclonic Reactor	Dorr-Oliver	100	85,000	
		200	120,000	
Wet Oxidation	Sterling Drug	1,000	300,000	(Oxidation unknown)
	Zimpro Division	470	284,000	(High oxidation)
Flash Dryer and Incinerator	Combustion Engineering	400	300,000*	
	Raymond Division	600	330,000	
		1,000	375,000	
		2,000	460,000	
		5,000	700,000	
Cyclo-Burner	Sergent - Zurn	130	70,000	

*Prices included drying but not dewatering equipment. Delete 20% for special equipment and add 25% for dewatering.

TABLE 82

Capital Outlay Required for Incinerator Systems by Population Group(156)

Population	Average Incinerator System Capital Cost - (1968 Dollars)
250	Not applicable
750	50,000[1]
1,750	70,000[1]
3,750	120,000[1]
7,500	130,000[2]
17,500	345,000[2]

[1] Based on one shift operation

[2] Based on two shift operation

TABLE 83

Disposal by Filtration and Incineration(193)

Population Served	Cost* ($/dry ton)
100,000	60-90
500,000	50-75
1,000,000	30-50
2,000,000	25-40

*Activated sludge plants

Note: $/ton ÷ 0.9 = $/metric ton

TABLE 84

Total Disposal Systems- Comparison Table (201)

No.	Process	\$1000 Capital	\$1000 O&O	Feasibility Tech.	Feasibility Econ.	Tech. Rank
1	Farm	2,294	262	Good	Exc.	2
2	Lagoon	2,820	353	Fair	Good	3
3	Dehydration	3,900	419	Good	Good	1
4	Rotary Kiln	2,334	479	Poor	Fair	7
5	M.H. Incin.	3,471	534	Poor	Fair	6
6	Porcupine	3,887	537	Fair	Fair	4
7	Fl. Bed. Incin.	3,887	551	Poor	Fair	5
8	AST	3,750	634	Poor	Poor	9
9	Compost	4,997	687	Poor	Poor	10
10	Flash Dry	4,640	781	Poor	Poor	8

O&O = Owning and Operation

TABLE 85

Costs for Disposal of Water Treatment Sludges (202)

Location	Sludge Type	Processes*	Total Disposal Cost		
			\$/mg	*\$/ton of dry solids*	*\$/ton of lime*
Austin, Texas	Lime	C	25.10	25.10	—
Boca Raton, Fla.	Lime	T, VF	16.00	16.00	—
Dayton, Ohio	Lime	T, C, R	2.20†	1.50†	0.79†
Goleta, Calif.	D. Earth	VF	8.52	95.10	—
Lansing, Mich.	Lime	T, C, R	2.00	6.15	2.60
Lompoc, Calif.	Lime & D. Earth	S	24.20	4.89	—
Miami, Fla.	Lime	T, C, R	6.95†	10.55†	5.08†
Minot, N. D.	Lime	T, VF	21.80	7.29	—
New Britain, Conn.	Alum	L	3.30	39.00	—
Somerville, N. J.	Alum	L	0.09	2.00	—
Sunol, Calif.	Alum	S	1.18	56.60	—
Willingboro, N. J.	Alum	L	4.90	33.50	—
Model Studies	Alum	T, VF	25.40	122.00	—
	Lime	T, VF	12.35	12.35	—
	Lime	T, C	11.40	11.40	—

* Process Symbols: C = Centrifuge, L = Lagooning, R = Recalcination, S = Sand Beds, T = Thickening, VF = Vacuum filtration.

† Profit from recalcined lime.

cination is practiced, substantial profits have been reported. Recalcination of lime sludge offers many advantages; however, its application is limited to only large softening plants, where ground water is low in magnesium. Results of the study made by Adrian and Nebiker (202) on the costs of disposal of water treatment sludges are presented in Table 85. It is apparent that application of mechanical thickening and dewatering facilities adds significantly to the cost of sludge disposal. However, their use is justified where recalcination is employed.

In summary, it appears that transporting liquid digested sludge by pipeline and its application on farmland as well as sandy soil and strip mine spoils is the most economically and ecologically viable disposal and utilization method. Application of dried sludge on farmland as a soil conditioner and fertilizer is a satisfactory disposal method. It may not be economically feasible if a mechanical dryer is not employed or an adequate local market for sale of the dried product is not available. Finally, sludge from water treatment plants is not too costly to dispose of; furthermore, recalcination of the water softening plant sludge has been shown to be an attractive and economical disposal method, where applicable.

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